The responses of diatoms to the influx of tephras into lacustrine environments

---

A thesis
submitted in partial fulfillment
of the requirements for the degree
of

Master of Science in Geology

by

Isaac Ronald Burwell

University of Canterbury
2003

Lake Pupuke, Auckland, New Zealand

Abstract

The aim of this research is to determine the response of diatoms to the deposition of tephras into lake environments. This is achieved by conducting high-resolution sampling of cores extracted from Lake Pupuke and Pukaki Crater; two maar lakes located in the Auckland Volcanic Field, and by analysing the diatom floras directly above and below selected tephra beds.

Tephras were selected for differing composition and thickness. Nine tephras were selected: four TVZ rhyolitic tephras, two Taranaki Volcano andesitic tephras, and three locally derived AVF basaltic tephras, ranging from 2 mm to 20 cm in thickness.

Eight of the sections record changes across the tephra bed; however, the mechanisms of response are not consistent between tephras of different composition or thickness.

The most common diatom recorded at both sites is *Cyclotella stelligera*, and in a majority of the sections, tephra input increases the dominance of this taxon. Tephra input has no impact on many environmental variables, e.g. the pH, salinity, nitrogen availability and oxygen saturation levels of the lake waters. Trophic status is most readily altered by the influx of tephra, generally recording a reduction in nutrient levels above the tephra.

The most common mechanism of response, recorded in three sections, is a reduction in phosphorus after tephra input probably due to the sealing off of underlying sediments by the tephra layer, thereby blocking the recycling of P from pre-tephra deposits. Other responses include effects associated with the physical properties of tephra particles interacting with diatom habitats, i.e. smothering of epiphytic habitats, and decreased turbulence in planktonic environments. Tephra also alters the relationship between *Synedra ulna* and a teratological variety of *Synedra ulna* v *spathulifera*. Suprisingly, thickness and chemical composition do not influence the response of the diatom assemblage.

Five of the nine sections also indicate that the tephras sank through the underling sediment, coming to rest up to 1.75 cm below their original stratigraphic position. This is recorded as an offset between the tephra depth and the depth where changes in diatom assemblage are recorded. The most likely mechanism appears to be grain-by-grain dissemination of tephra particles through the unconsolidated sediment at the sediment/water interface. Thickness and chemical composition of tephra do not appear to influence these events.

The identification of displaced tephras has major implications in all paleoenvironmental reconstructions which utilise tephrachronology and tephrastratigraphy as dating and correlating tools. In particular, tephras may not constitute absolute time markers.

Table of Contents

List of Figures

List of Tables

Acknowledgements

I would firstly like to thank my supervisor, Jamie Shulmeister for the endless support, discussions and proof reading. Thank you for coming up with a good idea at the start, even though where I am now is not where we envisaged I would be.

I would also like to thank Margaret Harper, from Victoria University for teaching me the wonderful world of diatoms. Without your assistance all that time ago, this thesis would have been a great deal shorter. Also, thank you for your patience in answering my many inane questions.

Many thanks to Jane Guise for all the help in the lab; to Kerry Swanson for instructing me on photomicrographs; and to Stephen Brown for the geochemical analysis. To John Carter, of Victoria University, thanks for being so accommodating of my very short-notice core stealing visits.

A special thanks to all the geology faithful: Andrew, Tanya, Sarah, Vicky, Andrea, Scott, Emma, Erica, Kerry, Grim, Eric, Linda, Tim, Beatrice, and all the people on the 4th floor, including the wannabes. With an extra-special thank you to Andrew and Tanya for making it all so much fun. We have been together a very long time, and it all seems worth it now.

I would also like to thank Tom, Helen, April, Alwie and Maia for keeping me warm, dry and fed, and for always making home life interesting, and Sue, for drunken joys.

Last, but by no means least, I would like to thank Angela and Rabbit. Thank you for the giggles and the cuddles. Thank you for being there always, and helping whenever possible, especially when I needed a beer.

Chapter one: Introduction

1.1 *General Introduction*

A fundamental requirement of paleoenvironmental investigations is the ability to date and correlate between sites, both locally and regionally. In regions with active volcanism, the most popular method is the use of tephrochronology and tephrastratigraphy as dating and correlating tools. Tephras are ideal for this purpose because individual tephras are widespread, readily identifiable and easily dated.

The tephra record utilised in paleoenvironmental studies is mainly restricted to those preserved macroscopically, but at any given site, there are likely to be many more microscopic than macroscopic tephras. There are also tephras which were initially deposited, but are no longer preserved in the sedimentary record. The information that that could be contributed by these non-macroscopic tephras is normally lost to the paleoenvironmentalist.

Tephras affect the lakes that they are deposited into, causing both physical and chemical changes. Organisms inhabiting the lake will respond to these changes, and may preserve a record of these events independent of the tephras themselves. It might be possible to identify tephric events simply by examining the patterns of biological response.

The basis of the current research is to determine whether systematic patterns of diatom response can be identified from lake sediments across tephra event horizons. If this can be achieved, it may be possible to develop a predictive tool for recognising microscopic and/or non-preserved tephras in lake sediments. Such a tool would have widespread paleoecological and tephrastratigraphic applications.

1.2 *Aims and Hypotheses*

The primary aim of this project is to investigate the response of diatoms to the input of tephra into a lacustrine environment. This is achieved by high resolution sampling

of cores extracted from maar lakes in the Auckland Volcanic Field, and analysing the diatom floras across tephra beds.

This research is part of a broader study program investigating the plaeoclimatic information recorded in maar lakes from the Auckland region (e.g. Hägg, 2002; Pepper, 2002).

This hypotheses being tested relating to the impact of tephra on lacustrine diatom floras are as follows;

1. Tephra events will impact on diatom floras.
    a. Changes in water column chemistry produced by the input of tephra will be the predominant process which control any response of the diatoms.
    b. The greater the thickness of tephra, the greater the effect on the diatoms.

1.3 *Thesis outline*

This research summarises the state of knowledge on the use of diatoms in paleoenvironmental reconstructions, the effects on diatoms of different nutrients and chemical compounds, and how these will influence the diatom assemblage of a lake if they undergo changes (Chapter 2). Also discussed in Chapter 2 are the properties of volcanic tephra, and the potential effect tephra can have on diatoms, and a short overview of the main volcanic centres in New Zealand, with specific reference to the tephras recorded in the two sites, concentrating on the geochemical make characteristics of the respective tephras. Chapter 3 gives an overview of the previous work on the response of diatoms to the input of tephra into a lake environment, outlining the principal causal mechanisms reported. Chapter 4 describes the sites investigated in this research, Lake Pupuke and Pukaki Crater, and the methods used in extracting the core, preparing the samples, counting the diatoms, and in analysis of the data. Chapters 5 & 6 present the results from the analyses. Chapter 7 discusses the mechanisms controlling diatom response to tephra input into lakes, and the implications for paleoenvironmental research.

Chapter two: Background

2.1 *Introduction*

This chapter will outline the background information relevant for this research. This includes the application of diatoms in paleoenvironmental work, and the role different physical and chemical variables have on the composition of the diatom assemblage inhabiting a lake. Also, the likely effects of tephra input on the lake environment, and how this may be represented by the diatom flora. The second part of this chapter outlines the different volcanic sources preserved within the Lake Pupuke and Pukaki Crater cores, and the geochemical makeup and distribution patterns identified.

2.2 *What is a diatom?*

Diatoms (Class Bacillariophyceae) are microscopic algae abundant in almost all aquatic environments where light is sufficient to support photosynthesis, the only exceptions being the very hottest and most hypersaline waters (Patrick & Reimer, 1966; Round *et al*, 1990). The number of diatom species is not known, but using modern species concepts, estimates in the region of 10^5 are common (e.g. Mann & Droop, 1996). The most characteristic feature of diatoms is the silicic cell walls, composed of two valves, which together form a frustule (Fig. 2.1). Taxonomically, the diagnostic features of diatoms are their size, shape and sculpturing detail of their cell walls (Stoermer & Smol, 1999). Because the cell walls of diatoms are composed of resistant opaline silica, they are readily preserved in lake sediments, and have specific environmental requirements so can be used in recreating past environments.

Diatoms have been studied since 1791 when the first diatom genus was described, though it was initially identified as an animal (Muller, 1791 in Round *et al*, 1990). The identification and classification of diatoms continued at a low level of activity until the 19th century, when advancement in microscope and microscope lens technology improved to a point where detailed studies of organisms as small as diatoms could be undertaken with confidence (e.g. Cleve, 1895). After these early

years in which developing classification and identification systems for diatoms dominated scientific research, attention changed to focus on their role as indicators of environmental change within sediment records (e.g. Cleve-Euler, 1922), diatom ecology (e.g. Cleve, 1894-1895), and as indicators of water pollution (e.g. Kolkwitz & Marsson, 1908), and these foci have continued to the present (e.g. Gasse, 1987; Hall & Smol, 1992; Telford & Lamb, 1999; Barker et al, 2000).

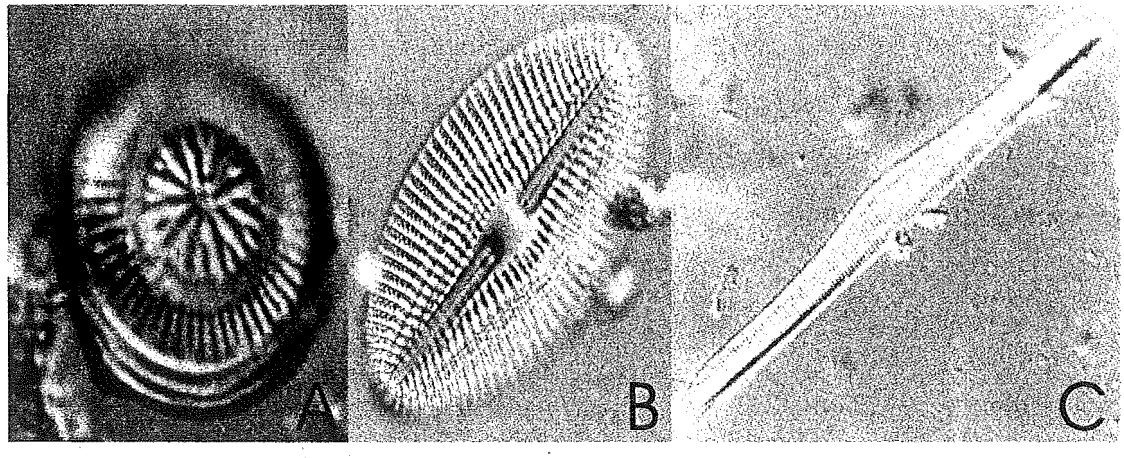


Figure 2.1: Examples of diatom taxa (A: *Cyclotella stelligera*, B: *Cocconeis placentula*, C: *Rhopalodia novae zealandiae*)

2.3 *Role of diatoms in paleoenvironmental reconstructions*

Diatoms are among the most abundant and diverse components of algal assemblages in lakes (Hall & Smol, 1999), and occupy a broad range of environmental settings (Patrick, 1977). The diatom species composition in a lake is related to chemical (pH, dissolved organic carbon (DOC), nutrients and salinity) and physical (temperature, light, turbidity and turbulence) variables. As individual diatom species have specific environmental preferences and are readily preserved in sediments, the long-term environmental status of a lake can be inferred by the investigation of diatom assemblages preserved in the lake sediments. The major factors that affect the composition of a diatom assemblage include:

2.3.1 Temperature

The influence of temperature on diatom growth was the subject of some of the earliest studies on diatoms (e.g. Husdedt, 1956). These studies showed that in temperate zones, changes in temperature (generally reductions) were the principal environmental control on the production of algal biomass (Stoermer & Ladewski, 1976; Patrick,

1977). Although studies showed that individual diatom species had quite large temperature tolerances, the dominance of a single species was closely correlated to temperature (Patrick & Reimer, 1966; Patrick, 1971). Temperature can also have indirect effects on diatom communities. Temperature controls the amount of silica present in the cell walls of diatom, as silica is more soluble in warmer water (Patrick & Reimer, 1966). In addition, the viscosity of water decreases in high temperatures which can affect the ability of planktic diatoms to remain buoyant (Patrick, 1977). More recent studies have shown that it is difficult to distinguish between temperature-induced changes and other physical and chemical variables because temperature is itself a major influence on these other variables operating within lakes (e.g. Battarbee, 2000; Anderson, 2000).

2.3.2 Light

Light is very important to diatoms because it regulates photosynthetic activity, and it therefore plays a significant role in determining species composition (e.g. Reynolds, 1984; Grover, 1988). The depth to which light can penetrate into a lake controls the depth of the euphotic zone, which is the region in which net photosynthesis takes place (Patrick & Reimer, 1966). The depth of the euphotic zone is controlled by the intensity of the penetrative light and the amount and properties of suspended particles in the water column. Water column transparency, which is influenced by light, also controls the range of habitats available for benthic diatom communities (Battarbee *et al*, 2001).

Studies have shown that diatoms have varying requirements for the amount, intensity, and duration of light necessary for optimum growth (e.g., Verdiun, 1952; Maberly *et al*, 1994). Planktonic communities composed of specific diatom genera inhabit different depths in the water column (Verdiun, 1952), which is believed to be related to light penetration, although the exact role is not known, as other variables probably also influence diatom depth optima. As for temperature, the effects of light are difficult to separate from other influences such as nutrient content, since their effects are not independent and are difficult to quantify from sediment records (Patrick, 1977).

2.3.3 Turbidity and turbulence

Turbidity and turbulence predominantly affect planktonic diatom taxa. This is because planktonic diatoms require turbulence for buoyancy purposes (Reynolds, 1982; 1984). Turbidity is important because it can reduce the amount to light present in the water column (Patrick & Reimer, 1966). Maar lakes have very low water-induced current because of small inflow and outflow. Therefore, wind-induced current is the main method by which turbulence is produced in these lakes and they are less well mixed than other lakes (Hoare & Spigel, 1987). The geography and climate of the surrounding region is important in determining the level of turbulence, as this will control the wind patterns present on the lake surface (Battarbee *et al*, 2001). Additionally, the bathymetry will control the properties and behaviour of turbulence at depth (Hoare & Spigel, 1987).

2.3.4 Diatoms and nutrients

Nutrient status is one of the most important environmental variables controlling composition of diatom floras (Hall & Smol, 1999). Therefore, understanding the role of nutrients on diatom taxa is important in determining past lake conditions, and the effects of any perturbations on the lake ecosystem, such as the influx of tephra. Individual species have specific optima and degrees of tolerance for nutrient concentrations, supply rates and ratios (e.g. Patrick & Reimer, 1966; Tilman, 1977; Tilman *et al*, 1982; Round *et al*, 1990; Hall & Smol, 1992; Christie & Smol, 1993; Fritz *et al*, 1993; Van Dam *et al*, 1994; Bennion *et al*, 1996). Nutrients commonly required by phytoplankton are C, H, O, N, P, S, K, Fe, Mg, Ca, Na, Si, Zn, Mo, Cu, B, Mn and Co (Patrick, 1977; Pridmore, 1987), of which N, P and Si are vitally important for diatoms. For the majority of algae, N, in the form of ammonia or nitrates, and P, are the dominant limiting nutrients, but for diatoms, the availability of Si is also significant because it is required for cell wall formation (Schmid *et al*, 1981). The foremost method by which these three nutrients control the diatom species structure is through resource competition (Abella, 1988). Some species of diatoms are more successful competitors for certain nutrients than others. Because of this, resource competition represented in the form of ratios between different nutrients (e.g. Si:P) is used as a proxy for interpreting diatom responses to changes in nutrient concentration in lakes (Tilman, 1977; Tilman *et al*, 1982). The ratio of silica to

phosphate appears to be the most useful discriminant (Tilman *et al*, 1982), although N:P is also important (Saros & Fritz, 2002).

10-72% of a diatom cell is composed of silica (Schmid *et al*, 1981), and Si is required for growth (Patrick & Reimer, 1966; Darley, 1977). Additionally, silica is required for several metabolic processes (Round *et al*, 1990). The main source of silica in lakes is through weathering of soils in the catchment and internal recycling of silica from sediments (Battarbee *et al*, 2001). Therefore, under stable conditions the percentage of silica does not change significantly through time in a lake environment.

Phosphorus is a major limiting nutrient for diatoms because it regulates aquatic productivity (Patrick, 1977). As well as direct effects on diatoms, a change in the phosphate content in a lake can have indirect affects on both pH and alkalinity (Lotter *et al*, 1998). Recycling from lake sediments is the main method by which lakes obtain phosphate.

Nitrogen is a dominant nutrient for all algal communities as it regulates primary productivity (Hill, 1975). Nitrogen is most useful for diatoms in the form of ammonia or nitrates (Patrick & Reimer, 1966), and the main source of these types of nitrogen in a lake is from runoff from the surrounding catchment. The form in which nitrogen is found in lake waters is dependant on pH, with a pH lower than 7 favouring nitrogen in the form of nitrates or ammonia, whereas when pH rises above 7, nitrogen tends to form ammonium hydroxide, which can be toxic to diatoms, so is therefore not readily utilized (Patrick, 1977).

2.3.5 Other chemical factors

2.3.5.1 pH

For freshwater environments, pH is believed to be the most significant variable influencing species composition (Husdedt, 1937; 1939; Battarbee *et al*, 1999). Although, pH has been statistically shown to explain a majority of variance in diatom assemblages in some types of lakes environments (generally soft-water lakes) (Battarbee *et al*, 1999), the mechanism by which pH affects individual diatom species is not understood (Battarbee *et al*, 2001). pH is known to influence nutrient availability, by affecting the solubility of metals, especially those toxic to diatoms (Fig. 2.2) (Foth, 1990; Saros & Fritz, 2002). This dictates that phosphorus, for

example, it most readily available in circumneutral waters, from 6.5 to 7.5, but also has high availability in very alkaline conditions, with pH's above 8.5. Nitrogen, another important nutrient, is also available in circumneutral conditions; ranging from 6.0 – 8.0, but is not readily available in highly alkaline environments (Foth, 1990). pH also affects the carbonate-bicarbonate balance found within lakes (Battarbee *et al*, 1999; Saros & Fritz, 2002).

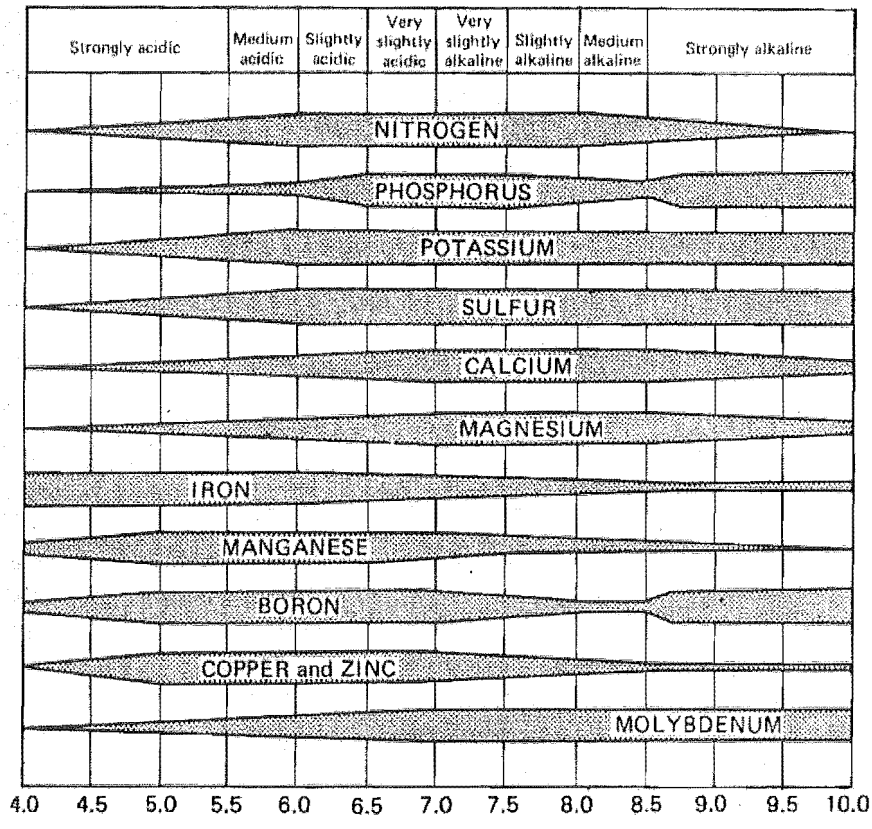


Figure 2.2: General relationship between pH and Solubility of nutrients (Source: Froth, 1990)

2.3.5.2 Dissolved Organic Carbon

In some lake settings (usually acidic lakes), DOC has been shown to explain the majority of diatom variability (Battarbee *et al*, 2001). Interestingly, DOC has been shown to work independently of pH and other variables (Korsman & Birks, 1996), although the precise relationship has not been determined (Battarbee *et al*, 2001).

2.3.5.3 Salinity

The relationship between salinity and diatom species composition has not been constrained (Fritz *et al*, 1999). Salinity, like pH, is known to influence resource utilisation, and therefore can potentially play a role in the structure of diatom

communities (Saros & Fritz, 2002). Presently, it can not be determined whether distributional patterns of diatoms are the result of salinity directly or whether they are caused by the combined affect of multiple physical and chemical parameters (Fritz *et al*, 1999; Battarbee *et al*, 2001).

2.3.6 Role of lakes in paleoenvironmental reconstructions of volcanic events

Theoretically, sediment flows continuously into lakes from the surrounding catchment and through aeolian influx (mainly dust). This means that lakes can continuously accumulate sediments that record environmental information, reflecting both catchment-wide and in-lake processes caused by natural 'background' development, and any perturbations that occur in the system (Grönlund & Kauppila, 2002). Maar lakes are especially useful in recording lake processes because they are generally deep (>50 m), with very small catchments, mostly confined to within the tuff-ring walls (Negendank & Zolitschka, 1993b). This results in only a limited amount of terrigenous sediment being transported to, and deposited in, the lake. This means that terrestrial sediment does not override the system and that the lake environment can remain stable for long periods of time (Creer & Thouveny, 1996). This results in biogenic sedimentation being equal too, if not greater than, sedimentation of terrestrially supplied material. Because terrestrial sedimentation is restricted, the lake does not become infilled, so very long sedimentary records can be preserved within the lake (Negendank & Zolitschka, 1993a).

Since many lakes are situated within the range of air-fall deposits of volcanoes, they can record ancient volcanic eruptions. From studying the sediments immediately above and below a lake record of such an eruption, information on the responses of the biological community to the influx of volcanic products can be determined. The most common volcanic product to be preserved in a lake environment is tephra. If a lake is outside the blast-zone, yet inside the airfall zone of the volcanic eruption, the lake will receive tephra, which will land in the lake and settle to the bottom, thereby appearing to form an in situ sedimentary unit. Conversely, if a lake is situated within the blast-zone of a volcanic eruption, it will be subjected to volcanic products and processes which will (often) irrevocably alter the lake, leaving none or very little of the original lake in its initial state (e.g., Mt St Helens in 1980) (Baross *et al*, 1982).

The dispersal of airfall tephra from an eruption is not a simple or uniform event, with many factors controlling the rate, direction and distance volcanic ash will travel. The most important of these are wind strength, wind direction as well as eruptive style of the volcanic source.

2.4 *Properties of Volcanic ash*

Tephra is not a uniform substance, and refers to all pyroclastic ejecta or fragmental material that is blown into the air through explosive volcanic activity (Thorarinsson, 1981). Tephra can vary in mechanical and chemical composition, as well as size, during an eruptive episode from a single eruptive vent, as well as between volcanic regions (Shane, 2000). Individual tephra layers can be traced back to their source because each volcanic system produces magma and tephra with distinct chemical and physical properties (Larsen, 1981).

The method by which magma, and therefore tephra, is formed is known as magma vesiculation. This process is controlled by temperature, composition and the volatile content of the magma, which in turn controls the viscosity and surface tension of the erupted tephra (Heiken & Wohletz, 1985). The viscosity of the tephra is dominantly controlled by the percentage of silica in the erupting magma, and the silica percentage is used as the method of division for the different eruptive styles and products.

Compounds of silica (SiO_2) dominate the chemical structure of tephra; with aluminium oxides (Al_2O_3) being a distant second (Edmondson 1984; Shane, 2000). Although these two elements form the bulk of the chemical composition of tephra, many other elements can be found in smaller amounts. Other elements which are frequently important in tephra include oxides of Potassium (P_2O_5), Titanium (TiO_2), Iron (FeO_2, Fe_2O_3), Manganese (MnO), Magnesium (MgO), Calcium (CaO), Sodium (Na_2O), Potassium (K_2O, K_2O_5) and Chloride (Cl). Water is also present in tephra, sometimes accounting for more than 5% of weight.

Many rare earth elements (REE) and trace elements are also present in tephras in very small quantities (ppm). These include: Barium (Ba), Vanadium (V), Lutetium (Lu), Zinc (Zn), Uranium (U), Nickel (Ni), Thorium (Th), Ammonia (NH_3), Tantalum (Ta), Cesium (Cs), Chromium (Cr), Scandium (Sc), Rubidium (Rb), Copper (Cu), Lanthanum (La), Niobium (Nb), Neodymium (Nd), Lead (Pb), Thalium (Tl),

Terbium, (Tb), Ytterbium, (Yb), Selenium (Se), Arsenic (As), Yttrium (Y), Cerium (Ce), Samarium (Sm), Cadmium (Cd), Germanium (Ge), and Fluorine (F) (Edmondson 1984; Cronin *et al*, 1998; Shane, 2000; Felitsyn & Kirianov, 2002). The presence of REE and trace elements can assist in identification of tephra beds because the REE and trace element signature of individual tephras is distinct, which allows correlation between beds. Trace elements can also affect the diatom assemblage, either by providing key nutrients or toxicity (Patrick, 1977). For example, Zn, Pb, Cd, As and NH_3, if present in high concentrations are toxic to organisms, whereas trace amounts of V, Cu, Co, Fe, Mo and Zn, are tolerated and even necessary for growth (e.g. Edmondson 1984; Felitsyn & Kirianov, 2002; M. Harper, pers. comm., 2003). Silica, nitrogen and phosphate are the most important nutrients found in tephra (see section 2.3.4) (Felitsyn & Kirianov, 2002).

Input of tephra into a lake can have both mechanical and chemical effects on the environment (Barsdate & Dugdale, 1972). However, it is very difficult to separate the individual influence of these effects because they all work simultaneously in the lake environment during and after tephra deposition and it is their combined effects which produce the changes in diatom assemblages that are seen in the sediment record.

2.4.1 Mechanical effects of airfall tephra on lakes

The effect of a continuous, consolidated layer of tephra covering the lake bottom would be to produce a physical barrier between the pre-eruption sediments and post-eruption deposits. This could affect the lake ecosystem in two ways: firstly it could smother the habitat of benthic organisms, and secondly, it could reduce the rate of recycling of nutrients from the bottom surface sediments into the water column.

2.4.1.1 Smothering

Smothering of the lake bottom would have a significant effect on the habitat of epipelic, epipsamic, epilithic and epiphytic taxa because they would become covered by the settling ash (Hickman & Reasoner, 1998). Although all taxa in these habitats would become either wholly or partially buried by the tephra, the effects are not always damaging. For epiphytic taxa, the effects from the submergence of their habitat of living on waterweeds are generally found to be harmful since the waterweeds are generally killed, and until they recolonise, the habitat of these

epiphytic taxa is destroyed (Harper *et al*, 1986; Abella, 1988). Additionally, once the waterweeds do begin to re-inhabit the lake, pumice trapped along the shoots of the resurgent stems would produce a shade effect on the diatoms living below, which would hinder photosynthesis, thus extending the duration of negative impacts of tephra deposition on the epiphytic species (Harper *et al*, 1986).

For epipelic species, the thickness of the settling tephra is a major control on the response of diatoms to tephra input (Edmondson 1984), because the thickness of the tephra layer will determine the ease with which the diatoms will burrow through to the new sediment-water interface and colonise the new environment (Skille *et al*, 1983; Harper *et al*, 1986). Physical characteristics of the tephra layer, such as cohesiveness and angularity of the individual particles, are also likely to influence the ability of the diatoms to re-colonize. Tests have shown that epipelic diatoms are able to burrow through up to 5 cm of tephra material to reach the new sediment-water interface (Harper *et al*, 1986). This experiment showed that the grain size of the tephra was the dominant variable controlling the ease at which the diatoms could burrow through to the new surface. It was found that for fine ash, diatoms readily moved up through the ash to the surface. In coarser ash, many diatoms were unable to move through the sediment (Harper *et al*, 1986). The duration of these effects depends entirely on the thickness and grainsize of the tephra (Harper *et al*, 1986). If the tephra is fine grained and only thin, then the duration of the effects on the benthic diatoms would be short, whereas if the tephra was thick and coarse grained, the diatoms may not be able to burrow through the tephra grains. If this occurred, then the impact on the benthic diatom community would be severe, and would continue until a new population of benthic diatoms were able to colonise the newly available benthic environment.

2.4.1.2 Recycling of lacustrine nutrients

A consolidated layer of tephra covering the bottom of a lake would reduce the rate of diffusion of remineralised nutrients from the pre-eruptive sediments by limiting the activity of micro-organisms which live on the lake bottom, and by blocking access to the nutrients (Barsdate & Dugdale, 1972). Most affected by this process would be phosphorus, because the majority of P present in lake waters is produced from recycling of sediments by micro-organisms (see section 2.3.4). Input of tephra into a lake can shut down the recycling of phosphorus from pre-tephra sediments by sealing

pre-tephra sediments by forming a continuous and consolidated layer of sediment across the lake bottom (Edmondson, 1984). This would be represented in the diatom record by a reduction in species that are poor competitors for P when it becomes limiting, and an increase in species which are good competitors for low amounts of P (e.g. Abella, 1988). The level of P depletion caused by this process has not been investigated (Barsdate & Dugdale, 1972), but the effect on lake water chemistry would depend on the nutrient status of the lake before the tephra is deposited. If the level of P in the lake water is low before tephra deposition, then further depletion of the P levels are not likely to cause major disruption to the water chemistry and therefore to the environment within the lake because the lake would be already be P-limiting (Telford, 1998). If, however, the lake contains a high level of P before the tephra is deposited, a major change in the water chemistry of the lake could occur because the amount of P supplied to the lake from the underlying sediments would suddenly drop off (Edmondson, 1984). This could cause the lake waters to become P-limiting, which would affect diatoms living within the lake as all diatoms have specific optimums and tolerances of P content (Hall & Smol, 1992). Diatoms which require high concentrations of P would be detrimentally affected and would decrease in abundance (Abella, 1988), while the populations of those taxa which require low levels of P would increase, filling the ecological niches vacated by the high-P requiring taxa. The magnitude of such shifts would depend on the concentration of P present in the lake before the tephra and how much P decreased across the tephra layer.

The suppression of nutrient recycling from pre-tephra sediments would affect the environment for as long as it takes for additional sediment to accumulate in the lake, and for micro-organisms to recolonise the newly formed sediment-water interface. New sediment would begin accumulating instantly, unless the lake is cut off from the flow from the catchment due to the tephra producing a major change in the water percolation and transport patterns in the catchment. The length of time until recolonisation of micro-organisms is complete is very difficult to quantify, but is unlikely to be an extended period of time, generally restricted to maximum of several years (Edmondson, 1984).

2.4.1.3 Recycling of terrestrial nutrients

During stable periods, a high percentage of the nutrients contained within lake waters originate from leaching of soil horizons in the lake catchment which are then transported into the lake in the form of runoff. If tephra blankets the surrounding area, a barrier could form which would prevent leaching of the pre-eruption sediments, and therefore alter the chemical makeup of the runoff, thereby altering the water chemistry of the lake (e.g. nitrogen) (Barsdate & Dugdale, 1972; Skille *et al*, 1983). Runoff in this scenario, instead, would carry nutrients leached from the tephra into the lake, causing changes in the water chemistry of the lake (Harper *et al*, 1986). Additionally, a very thick layer of ash over the ground could produce a change in the percolation patterns of water and therefore water transport into the lake (Edmondson 1984). While a considerable thickness of tephra deposited on the surrounding catchment may affect the flow of nitrogen into the lake, the long-term supply will not disrupted.

Effects experienced from a change in terrestrial nutrients being transported into the lake are unlikely to persist for an extended period of time (Barsdate & Dugdale, 1972). The nutrient status of terrestrial inflow will return to pre-tephra levels once all the tephra deposited on the landscape has been eroded away. Because the make-up of the surrounding soils will be altered due to the tephra, the nutrients supplied by erosion of the soils are likely to be different from pre-tephra products for an extended period of time. Although this will have an immediate effect on the diatom community, once the diatom assemblage has responded to the change in nutrient conditions, the influence will wane.

2.4.1.4 Turbidity

Because diatoms are autotrophic algae, their distribution is restricted to the photic zone (water depths down to about 200m depending on clarity) (Patrick, 1977). Turbidity produced by tephra falling into a lake can therefore have a detrimental effect on the diatom environment within the lake by cutting off the availability, penetration and clarity of light within the water column (Hickman & Reasoner, 1994). When tephra lands on the surface of a lake it will begin to settle out, with the larger particles settling out first. The finer particles will remain in suspension for longer, with the duration being controlled by the strength of wind at the lake surface, which

controls mixing (Hoare & Spigel, 1987). Turbidity is still produced during normal conditions, but with an input of tephra into the lake is that the amount of sediment being deposited in the lake, from both direct fallout and fluvial transport, can far exceed normal background levels. In shallow lakes, turbidity created by wave and water currents can persist to the very bottom of the lake. This will prohibit sediment, including tephra, settling on the lake bottom. This process could continue for a considerable length of time, and is an important consideration when investigating shallow lakes (e.g. Harper *et al*, 1986). This also will affect the turbidity, turbulence and therefore the clarity of the shallow regions of deeper lakes (Edmondson 1984).

The duration of tephra effects on water clarity are not well understood, but they are thought to only last for a few weeks at the most (Edmondson 1984). Again, this will depend on the depth and wind characteristics of the lake. After the Mt St Helens eruption of May 1980, deeper areas of Soap Lake experienced turbidity only briefly, with the water regaining its pre-eruption level of water clarity within a few days, whereas the shallow areas closer to shore took several weeks for normal water clarity conditions to return (Edmondson 1984).

2.4.2 Chemical effects from airfall tephra on lakes

2.4.2.1 Dissolution into water

The biological impact on diatoms of dissolved chemicals released into solution is also dependant on the characteristics of the receiving water (Barsdate & Dugdale, 1972). However, not all of these chemical elements will be present in a form that is soluble in water, so the amount released will be less than the percentage composition. This is a particular issue associated with silica (Cronin *et al*, 1998). A lake that is deficient in the chemicals present in the tephra will respond more to the addition of small amounts of dissolved material than a lake which is already rich in these nutrients (Edmondson 1984; Barker *et al*, 2000). Oligotrophic lakes are most likely to respond to nutrient input. The diatom assemblage will shift to accommodate the change in water chemistry (e.g. Barsdate & Dugdale, 1972; Haberyan, 1998). The diatoms inhabiting a nutrient-rich, eutrophic lake are likely to change only if a toxin is released (Edmondson, 1984).

Across an event such as the input of tephra into the lake, the levels of silica present in the lake water can vary significantly, whereas tephra input will contribute very little nitrogen into the water, as nitrogen is not a prominent component of tephra particles. Generally, input of tephra results in an increase in Si availability (e.g. Abella, 1988). This increase may result in a change in the resource competition relationships of the diatoms present, with silica losing its limiting status. For example, species of *Synedra* are very poor competitors for silica (Kilham, 1984; Kilham *et al*, 1986). This means that if silica is in limited supply in a lake, then *Synedra* species will struggle. However, if a tephra is deposited in a lake and silica is dissolved out of the tephra, the amount of silica in the lake will increase, and it may lose its limiting status. *Synedra* species should then increase in abundance.

Many elements present in tephra are known to be relatively insoluble in water, so only a limited level of enrichment is likely. Dissolution of phosphates, ammonia and nitrates from tephra sourced from the 1980 Mt St Helens eruption in the region of Lake Coeur d'Alene, Idaho was shown to have little or no impact on the water chemistry of the lake because of their relative insolubility (Skille *et al*, 1983). However, soluble compounds in tephra will be released into the environment after deposition. Analysis of a small rhyolitic eruption from Tolbachnik, Kamchatka, found that the amount of soluble forms of metals transported into the environment was 300 ton of Fe, 77 t Zn, and 47 t Cu (Menyailov & Nikitina, 1980). This represents a significant enrichment of the environment in these elements.

Trace elements found in volcanic ash are also leached out. Heavy metals can affect diatoms by producing aberrant specimens (Feldt *et al*, 1973; McFarland *et al*, 1997), and some metals are toxic to algae, which is likely to facilitate any changes recorded in the ecological status of the lake (Skille, 1983; Felitsyn & Kirianov, 2002). Abrupt changes in major and trace element concentrations across tephras have been recorded, which found that concentrations either increased or decreased exponentially up to 5 cm above the tephra (Hardardóttir *et al*, 2001).

The duration of effects from dissolution of nutrients from tephra is difficult to quantify. There will be an initial burst of nutrients leached out as the tephra enters the lake, but the supply of nutrients will decrease rapidly. While the tephra remains exposed on the bottom of the lake, dissolution will continue to occur. Once the tephra becomes buried by additional sediment, the rate of dissolution will decrease, but is

unlikely to stop completely. Low levels of dissolution will continue until the soluble fraction of the tephra has been completely removed (Edmondson, 1984).

2.4.2.2 *Organics from vegetation*

Ash loading on the terrestrial environment surrounding a lake will damage vegetation growing in these areas in three ways. Firstly, the physical effects of the weight of tephra landing on vegetation could cause it to collapse; secondly, vegetation can be smothered by a thick tephra (Hardardóttir *et al*, 2001); and thirdly, the abrasive character of pumice particles can produce significant damage to vegetation (Harper *et al*, 1986). This damaged material will quickly decompose and can then be transported into the nearby lake.

An additional source of nutrients for lakes resulting from volcanic eruptions is the release of inorganic plant nutrients from accelerated decay of plant material in the surrounding catchment caused by ash coverage (Harper *et al*, 1986). Decaying vegetation releases inorganic nutrients that under normal conditions contribute to the 'background' nutrient status within a lake; but a perturbation, such as a volcanic eruption, can result in a dramatic increase in the rates of these nutrients, especially phosphorous and nitrogen. The increase in such nutrients can result in increased eutrophication and a significant increase in lake productivity, and may produce a major shift in the diatom community structure (Hall & Smol, 1999).

The onset of any effects from these processes is not instantaneous. There is a lag-time for the tephra to damage vegetation. The vegetation has to then decompose and the released nutrients have to be transported to the lake. The duration is dependant on the proximity of vegetation to the lake, and the level of precipitation in the catchment. The duration of effects from chemical processes associated with the alteration of terrestrial nutrient transport on diatoms would, similarly be relatively short. Once the affected vegetation has decomposed, and the catchment recolonised with regenerative vegetation, the supply of additional nutrients would cease. Climate influences the duration with warmer, wetter climates responding more rapidly (Edmondson, 1984).

2.5 *Tephra sources*

In New Zealand, there are 5 major volcanic centres that have been active during the Quaternary; Taupo Volcanic Zone, which incorporates Taupo Volcanic Centre, Okataina Volcanic Centre and Tongariro Volcanic Centre; the Auckland Volcanic Field; Taranaki Volcano; and Mayor Island Volcanic Centre (Fig. 2.3). Tephras sourced from all these centres are found in Lake Pupuke and Pukaki Crater. The Holocene record from Lake Pupuke contains four tephras from the last c. 10,000 years, whereas Pukaki Crater has at least 80 tephras preserved from the lake over the last c. 100,000 years. Within the Pupuke core, the Rotoma tephra (Okataina), Tahua tephra (Major Island), Taupo tephra (Taupo) and Rangitoto tephras (Auckland) are preserved and samples were taken from across them all. Only one of the tephras sampled within the Pukaki Crater core has been correlated to other known deposits, so therefore, not all the tephras have been named. However, the tephras sampled were the T5 tephra (Taranaki), T6 tephra (Auckland), Kawakawa (T4) tephra (Taupo), T3 tephra (Taranaki), and the T2 tephra (Auckland).

While tephrochronology has widespread applications throughout New Zealand for correlating volcanic eruptions and dating volcanic and other geologic events (e.g. Shane, 2000), geochemical data for all volcanic centres is not well constrained.

2.5.1 Taupo Volcanic Zone

The Taupo and Okataina Volcanic Centres are two of at least eight major rhyolitic caldera complexes that comprise the Taupo Volcanic Zone (TVZ) (Wilson *et al*, 1985), which is considered the most frequently active, large rhyolitic centre on Earth (Wilson *et al*, 1995). The TVZ is located 200-280 km south-southwest from Auckland, with its longitudinal axis stretching over 255 km. It has produced numerous large (>100 km^2) caldera-forming ignimbrite and plinian eruptions, forming the majority of the rhyolitic tephras and ignimbrites preserved within New Zealand (Wilson *et al*, 1995; Shane, 2000). Rhyolitic eruptions produce the most widespread tephra deposits, and expansive deposits have been recorded in surrounding marine basins stretching over 1000 km away from source during the last 1.6 Ma (Carter *et al*, 1995).

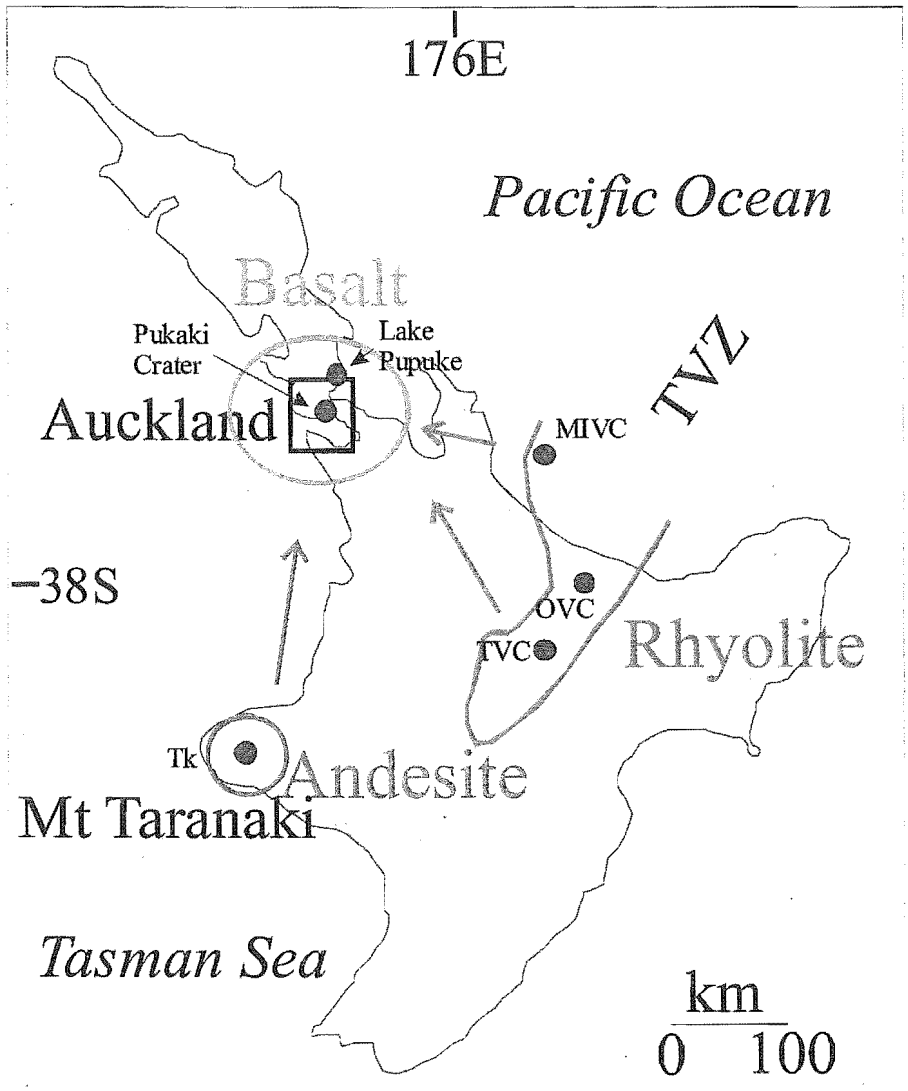


Figure 2.3: Map showing the location of the study areas: Lake Pupuke and Pukaki Crater. The red dots indicate the source areas for various tephra fall deposits identified in these sites. The orange circle indicates andesitic tephra source from Mt Taranaki, the green outline relates to basaltic tephra deposits, locally derived from the AVF. The blue line indicates the boundary of the Taupo Volcanic Zone (TVZ) and contained within this zone are three major sources for rhyolitic tephra deposits, the Taupo Volcanic Centre (TVC), the Okataina Volcanic Centre (OVC), and the Mayor Island Volcanic Centre (MIVC) (Source: Modified from Pepper, 2002)

The Taupo Volcanic Zone (TVZ) has been extensively investigated with respect to all areas of volcanology, therefore, the geochemistry of the Okataina and Taupo Volcanic Centres is well known. Distinguishing individual recent (post 22 ka) eruptive events from Okataina and Taupo using glass shard geochemistry, however, can be problematic because eruptions from these two centres during this period have been compositionally similar (Table 2.1) (Shane, 2000). Because of this, rare earth element (REE) and trace element composition analysis has been employed to distinguish between events from the two centres. In most TVZ tephras, REE and

trace elements vary inversely with SiO_2 content. Post-22 ka Taupo tephras characteristically contain higher levels of Sm, Eu, Tb, Lu, Hf and Sc, whereas Okataina beds can be distinguished by higher Th and Ba concentrations (Shane, 2000).

Table 2.1: Geochemical data for analysed tephras (Source: Sandiford *et al*, 2001; P. Shane, pers. comm., 2002)

	LAKE PUPUKE													
Sample Depth	Tephra	SiO_2	Al_2O_3	TiO_2	FeO	MnO	MgO	CaO	Na_2O	K_2O	Cl	P_2O_5	H_2O	n
33 cm	Rangitoto tephra	51.10	13.69	3.17	12.87	0.21	4.58	9.00	3.89	1.05	0.02	0.41	1.02	10
181 cm	Taupo tephra	75.29	13.18	0.28	1.85	0.11	0.27	1.53	4.50	2.82	0.17	n/a	3.70	10
509.5 cm	Tahua tephra	73.74	9.28	0.26	5.75	0.17	0.03	0.26	6.11	4.19	0.22	n/a	3.51	6
572.5 cm	Rotoma tephra	77.94	12.21	0.19	0.85	0.06	0.13	0.78	4.33	3.36	0.16	n/a	5.16	10
	PUKAKI CRATER													
Sample Depth	Tephra	SiO_2	Al_2O_3	TiO_2	FeO	MnO	MgO	CaO	Na_2O	K_2O	Cl	P_2O_5	H_2O	n
54.50 m	T2	46.1	16.52	3.08	12.58	0.18	3.88	10.45	5.35	2.05	0.11	n/a	1.42	20
54.815 m	T3 (Poto tephra)	65.29	17.11	0.76	4.34	0.23	1.52	3.29	3.28	3.9	0.29	n/a	2.25	14
54.865 m	T4 (Kawakawa tephra)	78.35	12.46	0.19	1.25	0.12	0.15	1.08	3.2	2.95	0.24	n/a	6.12	10
55.40 m	T6	47.33	17.64	2.72	10.87	0.22	3.47	8.64	6.32	2.64	0.14	n/a	1.47	20
61.02 m	T5	61.11	17.43	0.92	5.17	0.18	1.61	4.17	5.02	3.88	0.5	n/a	2.95	11

2.5.1.1 The Taupo Volcanic Centre

The Taupo Volcanic Centre is the southerly of the two dormant caldera volcanoes which dominate the TVZ (Fig. 2.3) (Wilson, 1993). The caldera collapse structure that the modern lake occupies was produced by the Oruanui eruption, of which the Kawakawa tephra is a product.

Kawakawa tephra

The eruption which produced the Kawakawa tephra (22.6 ka) was the largest Late Quaternary eruption in New Zealand (Froggatt & Lowe, 1990). At least 400 km^3 of pyroclastic material and 150 km^3 of ignimbrite material was produced (Carter *et al*, 1995), which was dispersed up to 1370 km to the southeast of the vent (Fig. 2.4). Locally, much of terrestrial New Zealand received some quantities of ash, with macroscopic remnants being recorded on the West Coast of the South Island (Mew *et al*, 1986), in Marlborough (Campbell, 1986), Canterbury (Kohn, 1979), and on the Chatham Islands (Hay *et al*, 1970; Mildenhall, 1976). Microscopic particles have also been identified in South Canterbury (Eden & Froggatt, 1988) and in Southland (McIntosh *et al*, 1988). Although the Kawakawa tephra is well represented in

terrestrial sites, it is believed that the majority of the pyroclastic material produced by the eruption fell at sea (Carter *et al*, 1995).

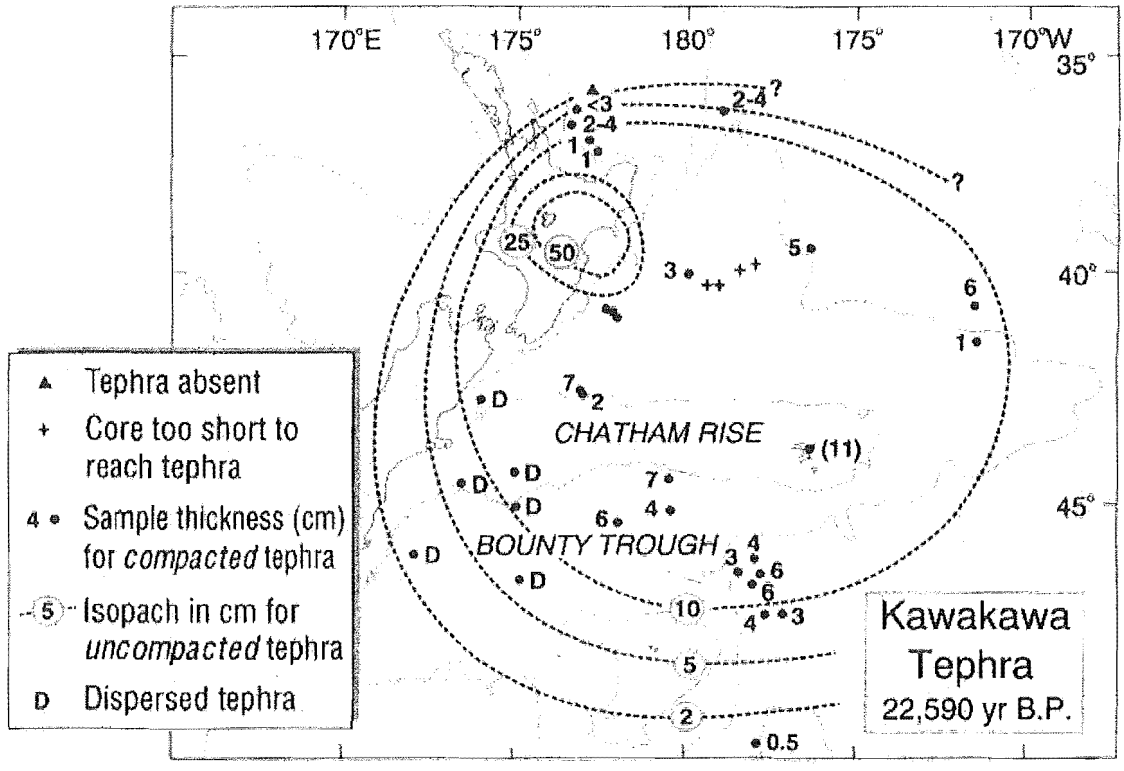


Figure 2.4: Estimated isopachs of uncompacted Kawakawa tephra (Source: Carter *et al*, 1995)

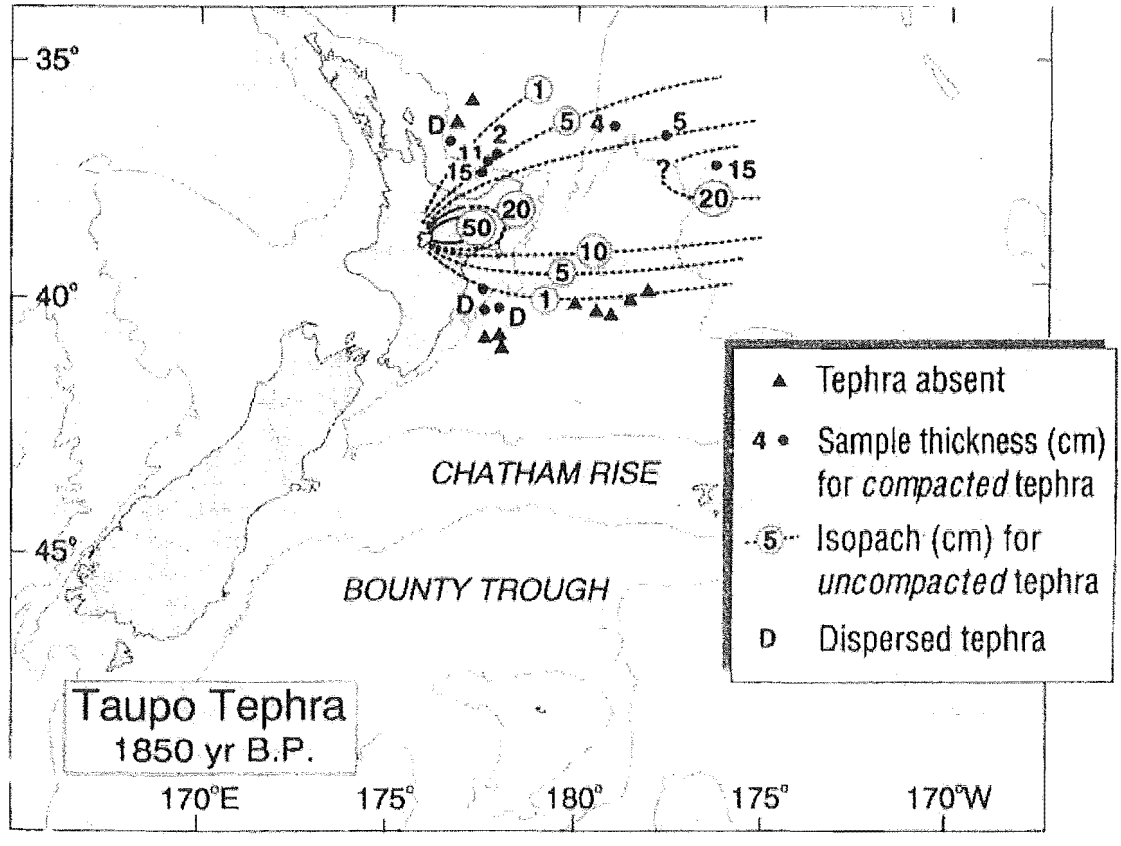


Figure 2.5: Estimated isopachs of uncompacted Taupo tephra (Source: Carter *et al*, 1995)

Taupo tephra

The eruption which produced the Taupo tephra (1.8 ka) ejected at least 50 km^3 of pyroclastic material and additional 70 km^3 of ignimbrite (Carter *et al*, 1995), making it the second largest eruption in New Zealand during the Late Quaternary. The eruption vent was located within the present Lake Taupo (Walker, 1980), and tephra was dispersed up to 660 km in an ENE direction (Fig. 2.5) Low-level wind patterns appear responsible for the distribution of the Taupo tephra towards the west, and its presence in Auckland sites (Nelson *et al*, 1986).

2.5.1.2 *The Okataina Volcanic Centre*

The Okataina Volcanic centre occupies the central section of the TVZ, and includes the large rhyolitic complexes of Haroharo and Tarawera, with others at Mt Edgecumbe, Okareka and Rotoma. During the last 22000 years about 80 km^2 of magma has been erupted from vents within the OVC.

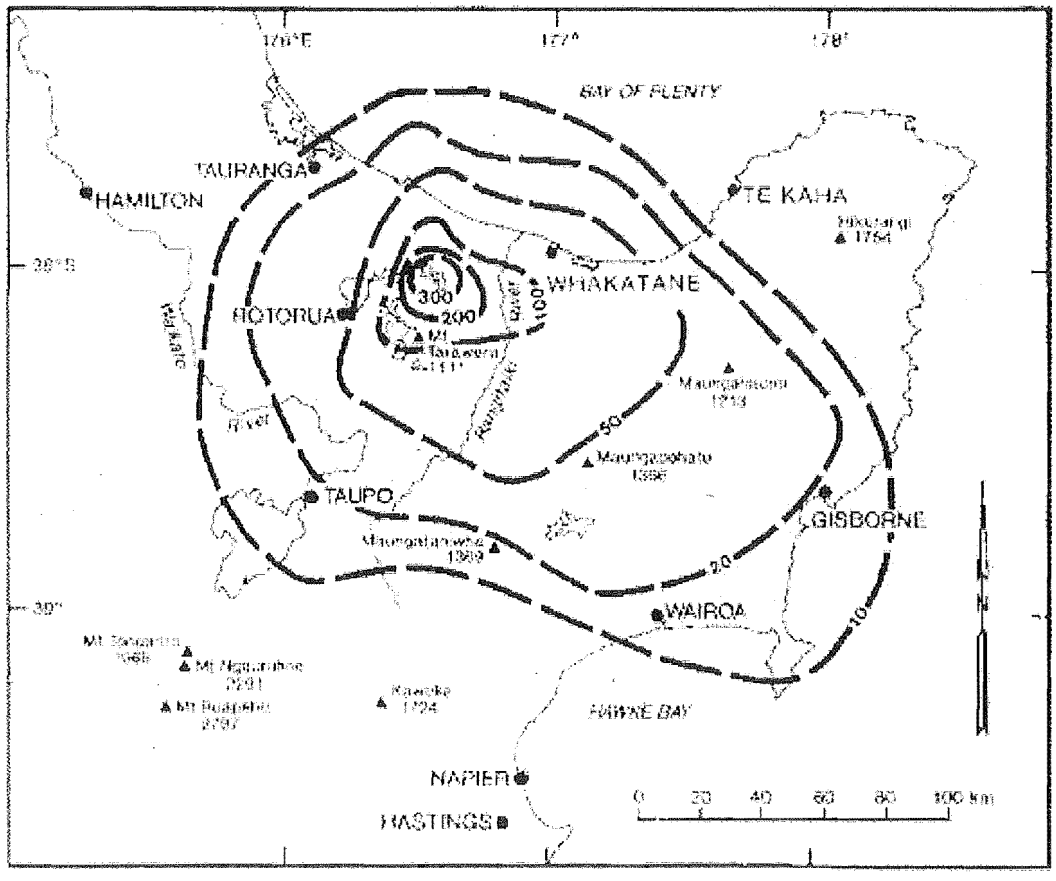


Figure 2.6: Dispersal pattern (in cm) of post 9.5 ka tephra from Lake Rotoma, Oaktaina Volcanic Centre (Source: Nairn, 1991)

Rotoma tephra

The Rotoma tephra was produced by an eruption from what is now Lake Rotoma, 9500 years ago (P. Shane, pers comm., 2002). 8km^3 of magmatic material was erupted, making it the third largest eruption from the OVC in post 21 ka. The distribution of the Rotoma tephra has not been the subject of much research; however, the extent of volcanic products from OVC has been mapped, with the dispersal pattern shown in Fig 2.6.

2.5.2 Mayor Island Volcanic Centre

Mayor Island is located 140 km southeast of Auckland and 20 km off the Corromadel/Bay of Plenty coast (Fig. 2.3). The peralkaline rhyolite volcano is isolated from the TVZ and is known to have been active for approximately the last 160 000 years (Hogg & McGraw, 1983).

2.5.2.1 Tahua tephra

The Tahua tephra is the only significant tephra produced by Mayor Island Volcanic Centre (MIVC), and is widely distributed across the North Island, including Coromandel Peninsula (Hogg & McGraw, 1983), Waikato (Lowe, 1988a,b), and Auckland (Newnham & Lowe, 1991; Newnham *et al*, 1999). Only four other post-64 ka tephra beds have been identified as originating from MIVC. These are recorded in deep sea cores (Pillans & Wright, 1992), and in North Island sites (Hogg & McGraw, 1983; Lowe, 1988a). The eruption of the Tahua tephra 7000 years ago (P. Shane, pers comm., 2002), is estimated to have produced 1 km^3 of pyroclastic material, with no ignimbrite or lava material being identified (Froggatt & Lowe, 1990). The dispersal pattern (Fig. 2.7) of the tephra is different to other rhyolitic eruptions, with the main axis of deposition being recorded towards the west (Hogg & McGraw, 1983; Sandiford *et al*, 2001).

The geochemical signature of the peralkaline Tahua tephra is such that it is easily identifiable in deposits. This is because it contains high FeO (>5 wt.%), high Na_2O (>5 wt.%) and low Al_2O_3 (<10 wt.%) concentrations relative to rhyolitic TVZ tephras (Shane 2000; Sandiford *et al*, 2001). Tahua tephra also contains significantly higher concentrations of all REE and trace elements than TVZ tephras, especially U, Th and Hf (Shane, 2000).

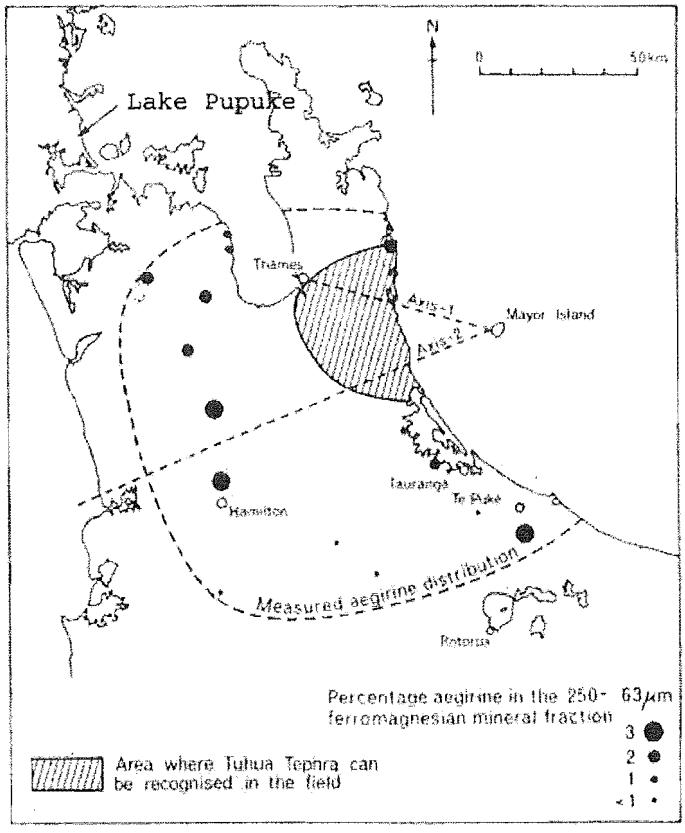


Figure 2.7: Onland distribution of Tahua tephra (Source: modified from Hogg & McCraw, 1983)

2.5.3 Taranaki Volcanic Centre

Mt Taranaki/Egmont is an andesitic stratovolcano located 275 km south of Auckland (Fig. 2.3), which first began eruptive activity at least 130 000 years ago, with the last period of activity recorded at about 1755 AD (Alloway *et al*, 1995). The andesitic Taranaki volcano erupts more frequently (approximately every 300 yrs (Alloway *et al*, 1995)) than those from the TVZ, and produces smaller volume tephras of limited dispersal (Shane, 2000). Although tephras produced from Taranaki volcano have a restricted dispersal, the north-easterly axis of dispersal results in tephra from Taranaki being widespread in Auckland (Sandiford *et al*, 2001; Shane & Hoverd, 2002).

Volcanic glass found in many tephra beds from Taranaki Volcano is heavily weathered or entirely absent (Shane, 2000). Therefore, a different technique is employed to identify these within sediments in addition to glass geochemistry; that of utilising various mineral phases (Cronin *et al*, 1996). The glass geochemistry of andesitic material found in New Zealand is very variable, especially with regards to SiO_2, which varies from 55-73 wt.% (Shane, 2000; Sandiford *et al*, 2001), which corresponds to andesite, dacite and rhyodacite. Taranaki tephras are also

characterised by high K_2O concentrations (>4 wt.%). A further issue that complicates Taranaki tephra identification is that distal tephra have higher SiO_2 and K_2O concentrations than proximal lava units (Shane, 2000).

2.5.3.1 Poto tephra

In near-source sites, the Poto tephra (20.9-22.7 ka) is not recorded as a single ash layer; instead, it comprises a closely spaced set of 15 coarse ash and lapilli beds, with a maximum thickness of 1.25 m (Alloway *et al*, 1995). The dispersal of the Poto tephra follows a south-easterly axis away from the volcano, but the exact extent of the unit is not well constrained (Alloway *et al*, 1995), however, the possible identification of the Poto tephra in the Pukaki Crater core greatly extends the known extent of the tephra across the North Island (Sandiford *et al*, 2001).

2.5.4 Auckland Volcanic Field

The Auckland Volcanic Field consists of about 50 basaltic volcanoes, dominantly comprising tuff rings and scoriaceous cinder cones (Fig. 2.8) (Allen & Smith, 1994). The age of the AVF is poorly constrained, but activity is believed to have begun 140-150 000 years ago, and is ongoing, with the Rangitoto eruption of 620 years ago being the most recent activity (Kermode, 1992). The AVF consists of volcanic centres covering an area of c.360 km^2. Eleven of the AVF volcanoes are tuff rings, 24 are complex "castle and moat" structures consisting of scoria cones surrounded by tuff rings, with the structure of the remaining volcanoes being undetermined (Allen *et al*, 1996). The volume of erupted volcanic material from individual centres is generally no greater than 0.4 km^3, except, Rangitoto, which produced 2 km^3, which comprises nearly half the total volume of erupted material for the entire AVF of 4.1 km^3 (Allen & Smith, 1994). Compositionally, the AVF is dominated by alkali basalts or basiniites, with transitional basalts, theolites, trachybasalts, phonotephrite, foidite and nepheninite also occurring (Heming & Barnet, 1986; Shane & Smith, 2000; Sandiford *et al*, 2001). All AVF volcanoes are monogenic (Kermode, 1992), as they represent a single episode of eruptive activity occurring over tens to hundreds of years (Allen & Smith, 1994; Cassidy *et al*, 1999). Strombolian, Hawaiian and Phreatomagmatic styles of eruptions are dominant in the AVF (Allen & Smith, 1994).

The geochemistry of the basaltic Auckland Volcanic Field (AVF) is the least well known of all the volcanic centres in New Zealand. The geochemical data obtained from the AVF shows that while the volcanoes have regionally similar values (41-50 wt% SiO_2); there can be significant chemical variation between different units of the same event (41-47 wt% SiO_2) (Houghton *et al*, 1999; Shane & Smith, 2000). Although between bed composition can differ, individual beds are usually homogenous with variation generally <0.5 wt. % (Shane & Smith, 2000). The chemical variation seen in AVF deposits, like andesites from Taranaki, is significantly greater than recorded in rhyolitic deposits (Sandiford *et al*, 2001). AVF glass is characterised by having high N_2O (4-7 wt.%) and K_2O (1.5-3 wt.%), and also contains high levels of Al_2O_3 (12-17 wt.%), FeO (8-14 wt.%) and CaO (10-12 wt.%) (Shane & Smith, 2000). Diagnostic geochemical fingerprinting of single eruptions within the AVF has been limited, so the correlation of known events with deposits is difficult. Although this method has been utilised for several of the major eruptions (dominantly Rangitoto), the majority of the smaller, older eruptions have not been investigated.

2.5.4.1 Rangitoto tephra

Tephra from the Rangitoto volcano has been identified at sites more than 5 km from source (Shane & Smith, 2000), but the older, smaller AVF eruptions are believed to only have been dispersed within 5 km (Sandiford *et al*, 2001). The irregular nature of AVF tephra dispersal is endorsed by having a basaltic tephra preserved in the Pukaki core, which is also recorded at Mt Richmond, 5 km to the northeast, while an additional basaltic tephra recorded in Pukaki core is not present at Mt Richmond (Sandiford *et al*, 2002).

2.5.4.2 T2 & T6

Tephras T2 and T6 are unnamed, and have not been correlated to a source volcano. T2 can be correlated with tephra T45/T42 recorded from the earlier drilling of Pukaki Crater (Pukaki 97) as described in Sandiford *et al* (2001). Possible source volcanoes for these tephras has been attempted very basically by comparing the known ages of the tephras to known ages of volcanic events in the AVF (Sandiford *et al*, 2001). Using this technique, the T2 event can be possibly correlated to six volcanoes, Mt St John, North Head, Pigeon Mountain, Mt Roskill, Little Rangitoto and Orakei Basin (Sandiford *et al*, 2001).

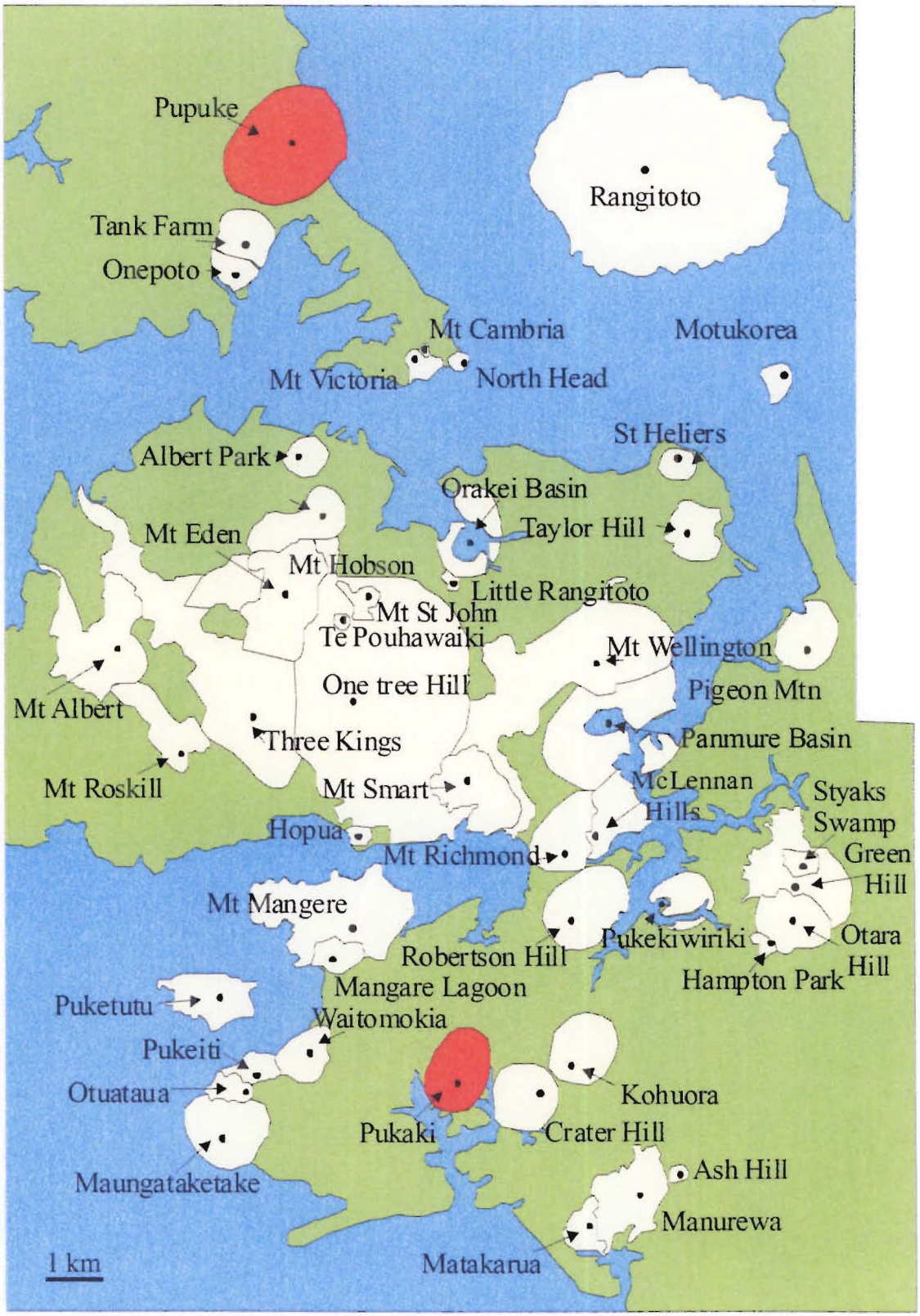


Figure 2.8: Volcanic craters within the Auckland Volcanic Field (yellow), the red craters are the two craters relevant to this study (Source: Modified from Pepper, 2002)

Chapter three: Previous studies on the impacts of tephra on diatom assemblages

3.1 *Introduction*

There have been a limited number of studies directly investigating the impact of tephra on diatom communities inhabiting lakes, although the majority of the studies have not been solely investigating the impact of the tephra. The vast majority of such studies have utilised core records. All of the previous studies investigating diatom response to tephra input have shown some form of response across the tephra, but the actual changes recorded have not been consistent. The majority have shown increases in diatom abundance and concentration immediately after input of tephra (Kurenkov, 1966; Barsdate & Dugdale, 1972; Harper *et al*, 1986; Hickman & Reasoner, 1994; 1998; Barker *et al*, 2000), but one study records a decline in abundance (Haberyan, 1998), and another shows no change across the tephra (Abella, 1988). In terms of diatom community composition, a majority of the studies record changes (Abella, 1988; Lotter & Birks, 1993; Birks & Lotter, 1994; Hickman & Reasoner, 1998; Telford, 1998; Telford & Lamb, 1999; Barker *et al*, 2000), but others do not (Hickman & Reasoner 1994, Haberyan, 1998). The mechanisms driving these changes vary from study to study, with the majority of authors favouring changing nutrient status, predominantly Si (Kurenkov, 1966; Barsdate & Dugdale, 1972; Abella, 1988; Brant & Bahls, 1995; Haberyan, 1998; Barker *et al*, 2000), while the physical smothering effects of tephra (Harper *et al*, 1986), and changing pH is also recorded (Lotter & Birks, 1993; Birks & Lotter, 1994). Additionally, several studies record the tephra input having no impact on the diatom assemblage (Hickman & Reasoner, 1998; Telford, 1998; Telford & Lamb, 1999).

The duration of effects from tephras is not consistent between sites, although the majority record changes in the diatom assemblage lasting for between 100-500 years (Barsdate & Dugdale, 1972; Harper *et al*, 1986; Abella, 1988; Lotter & Birks, 1993; Birks & Lotter, 1994; Hickman & Reasoner, 1994; 1998; Barker *et al*, 2000). Other

studies suggest shorter impacts in the zone of decades (Kurenkov, 1966; Haberyan, 1998) or years (Brant & Bahls, 1995).

What is apparent from all the sites investigated is that responses are site specific and will depend on the individual site and the conditions which exist in the lake at the time of tephra input. However, none of these studies separate effects from tephras of differing composition, which is investigated in this research. In this chapter, I will discuss the main studies which investigated responses of diatoms to tephra input. These will be grouped according to the dominant mechanism controlling the response.

3.2 *Change in Nutrient Status*

Lake Massoko is a maar lake situated in Tanzania, East Africa, with very similar dimensions to one of my study sites, Lake Pupuke. It is a relatively small lake, only covering 0.38 km^2, and has a small catchment area of only 0.57 km^2. Like all maar-type volcanic craters, the bathymetry of the lake shows very steep slopes, and a proportionally large near-flat bottom reaching a maximum depth of 38 m (Barker *et al*, 2000). The tephra recorded in the 2.7 m core recovered from Lake Massoko is not found in one coherent unit; instead at least four separate tephra layers are preserved within a 23 cm interval all separated by thin layers of gyttja. The first tephra was relatively thin (1-2 cm thick), with the last three tephras forming a near-coherent tephra horizon of 12 cm. This suggests that either the different tephras represent different eruptions, or that sediment mixing occurred after deposition (Barker *et al*, 2000).

The diatom record shows a dramatic change in both community structure and concentration levels across the tephras and these results in the largest change in the diatom community during the entire 4000 years length of the core. With regard to species composition, the dominant species before the tephra, *Aulacoseira granlata* v *muzzanensis* declined rapidly at the onset of the first tephra. It was replaced by *Synedra acus* + *vars* at this point as the dominant species. Although *A. granulata* v *muzzanensis* remained abundant after the deposition of the first tephra, with the input of the other tephras it never regained its pre-tephra dominance (Barker *et al*, 2000). The other species of *Aulacosira* recorded in the core (*A. granulata* and *A. granulata* v *jonensis*) are also adversely affected by the tephra input. *Synedra acus* + *vars* had not been encountered in the core until the input of the first tephra, but with the tephra

input, it became the dominant taxon with 60% of total abundance. Deposition of the additional tephras then further increased *S. acus + vars* dominance to 80-90%. The authors postulate that the process which produced the dramatic species composition change was a change in nutrient resource availability caused dominantly by sealing of underlying sediments by the coherent tephra layer (Barker *et al*, 2000). More specifically, *Synedra* is a vigorous competitor for P (Tilman, 1977), especially when it is limiting, and a poor competitor for Si regardless of it availability, whereas *Aulacoseira* requires high levels of both P and Si, and is a poor competitor for either when they are limiting (Kilham *et al*, 1986; Kilham & Kilham, 1990). This lead the authors to conclude that the first thin tephra was not sufficient to seal the underlying sediments, so P diffusion was not stopped and Si:P increased, which allowed *Aulacoseira* to survive. This was changed with the deposition of the additional tephras which were sufficient to seal the sediments and thus stopped P diffusion. This resulted in the level of P declining so that a population of *Aulacoseira* could not be supported, with *Synedra* able to out-compete it for the limited P available (Barker *et al*, 2000).

The shift in species composition continued for ~110 years until *S. acus + vars* declined in abundance. It is not a simple story of pre-tephra conditions being reinstated because *Aulacoseira* spp. did not become dominant once *Synedra* declined; instead *Navicula* cf. *seminuloides* became the dominant species. This indicates that nutrient levels did not recover to pre-tephra levels, and climatic change during this period is likely to be the cause, specifically an underlying decline in water balance (Barker *et al*, 2000).

Diatom abundance also rises sharply across the zone of tephra input, while diatom productivity increases sharply after the first tephra event, but declines immediately after, and does not show any change across the additional tephras. The authors postulate that the sudden, but short-lived increase in diatom productivity is the result of Si partly limiting the growth of *Aulacoseira*, so once the first tephra was deposited, it increased the level of Si available to *Aulacoseira*, resulting in an increase in productivity. This productivity increase was not able to be sustained after the additional tephras because P levels declined, thus *Aulacoseira* was not able to survive regardless of the elevated levels of Si available (Barker *et al*, 2000).

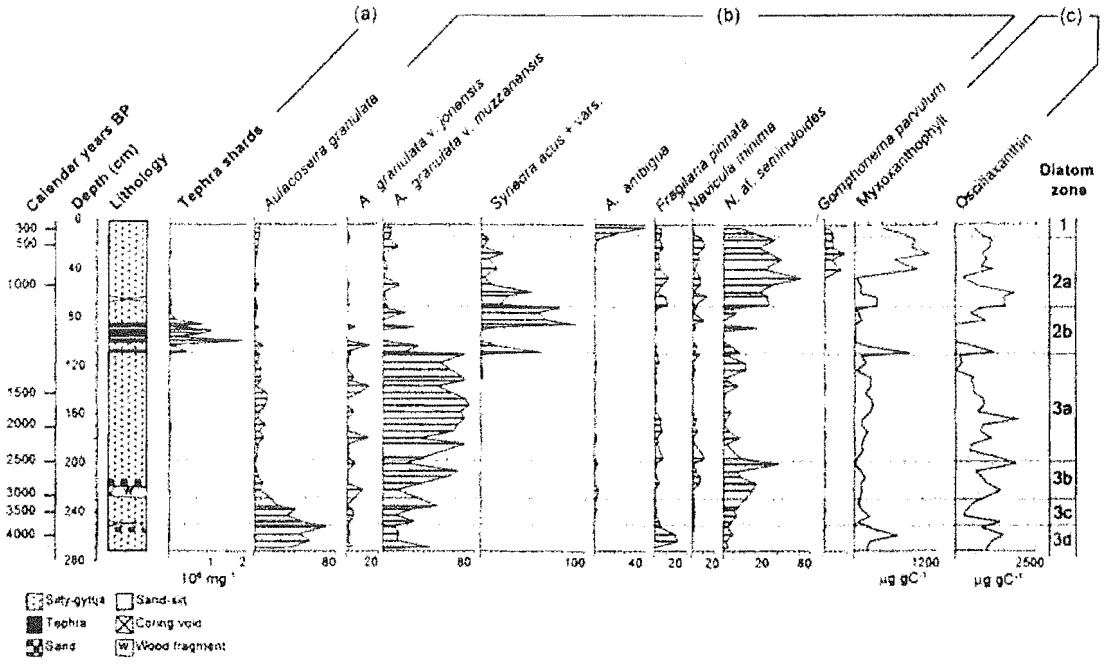


Figure 3.1: Summary of diatom, pigment and tephra data from Lake Massoko (Source: Barker *et al*, 2000)

In 1955, Mount Besynjanny, Kamchakta Peninsula, Russia, entered into an eruptive phase while the nearby Lake Asabatchye was being investigated several times a year for diatom concentration (Kurenkov, 1966). The limited data produced from the lake records considerable changes across the tephra, which was 20 mm thick in the lake. The data illustrates that the diatom concentration rose sharply after the tephra, with pre-tephra concentrations of $1x10^4$ cells/litre rising to $1x10^6$ cell/litre in the year immediately after the eruption (Fig. 3.1). Diatom concentration in the years following the tephra input did decline, but remained at levels one order of magnitude higher than what had been recorded preceding the tephra, until the last year sampled, 1964, when they returned to pre-tephra levels. Although, as 1964 was the last year sampled, it is not known whether this sample is representative of the record following this year. Kurenkov (1966) postulated that the elevated level of algae inhabiting the lake post-eruption may have been stimulated by increases in iron received by the lake from the tephra, as the other chemical variables analysed (CO_2, calcium, magnesium and total hardness) showed no significant changes across the event. This theory was based on investigations in nearby Uchinsky Reservoir, which recorded algal blooms related to increased iron levels in lake waters (Gusseva, 1952 in Kurenkov, 1966). Although it is apparent that favourable growth conditions did occur in Lake Asabatchye after the tephra was deposited, it is very difficult to discern whether iron was the dominant

factor in the increase in diatom concentration, although it is an important trophic indicator (Hall & Smol, 1999).

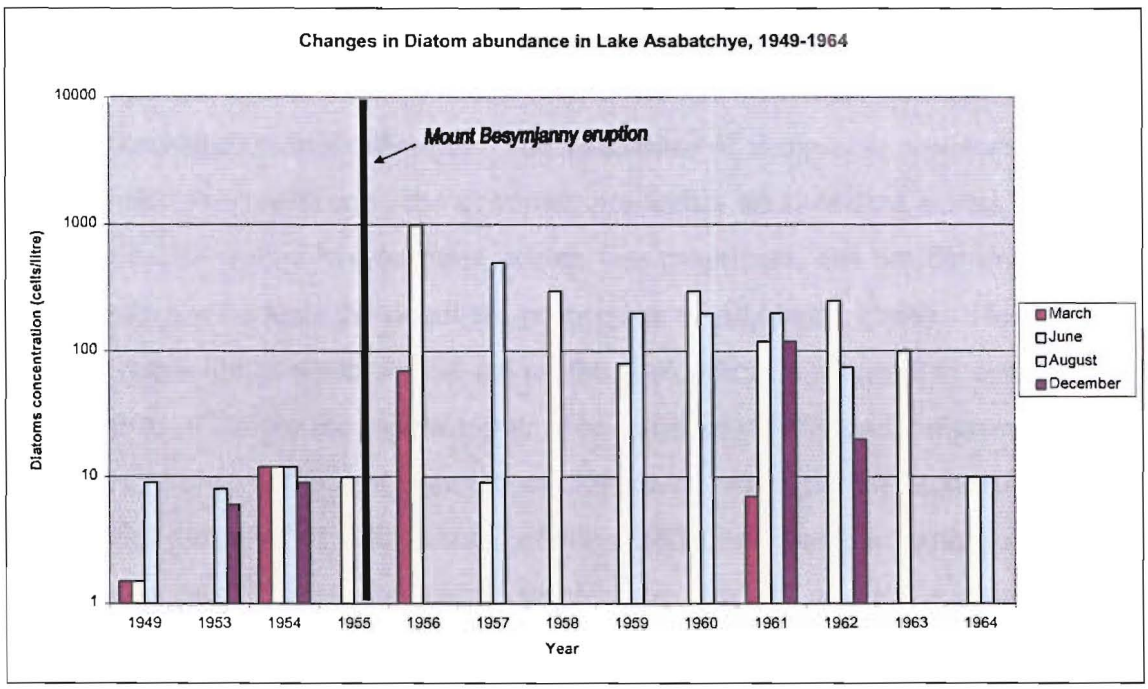


Figure 3.2: Changes in diatom concentration recorded across Mount Besymjanny tephra (Source: Redrawn from Kurenkov, 1966)

Barsdate and Dugdale (1972) investigated two Alaskan lakes (Upper Jennifer and Little Kitoi) and found several tephras preserved, including a 10 cm tephra representing the Katmai eruption of 1912. They found, as Kurenkov (1966) did, a considerable increase in diatom productivity following the tephra events. The lakes were considered to be still within the recovery period from the Katmai eruption of 60 years earlier, however, an earlier, smaller (1 cm) ash layer, recorded stimulatory effects of the tephra persisted for more than 100 years (Barsdate & Dugdale, 1972). They believed that Si enrichment of the lake waters from the tephras rather than other chemical and mechanical effects was responsible for the increase in diatom productivity (Barsdate & Dugdale, 1972).

While most studies investigate diatoms from all lake habitats, one study investigating changes recorded in Lake Washington was restricted to planktonic taxa (Abella, 1988). This study investigated whether changes in diatom community structure could be attributed to changes in the nutrient status of the lake across an ash layer sourced from Mt Mazama. The changes recorded across the tephra bed where different to those recorded by other authors (e.g. Kurenkov, 1966; Barsdate & Dugdale, 1972;

Harper *et al*, 1986; Hickman & Reasoner, 1994); in that diatom concentration and productivity did not show a large increase with input of tephra. In fact, a small decrease in diatom numbers was recorded across the tephra (Abella, 1988). Instead, a major shift in species composition was recorded, with the dominant planktonic species undergoing major changes. The abundance of *Fragilaria crotonensis*, and an unidentified *Meloseira* spp., the dominant pre-tephra taxa, decline across the tephra, and *Meloseira italica* v *subarctica*, which was prominent, but not dominant in pre-tephra samples became the dominant post-tephra taxa (Abella, 1988). The change in diatom composition continued 34 cm up the core, where it returned to a state almost identical to of before the tephra input. The duration of change is imprecisely dated with 14C dating yielding a duration of 560 years, while pollen accumulation rates provided a duration of 330 years. Abella (1988) believes that both these figures constitute periods far too long to be tenable, yet they are of similar length to other records (Harper *et al*, 1988). The major process responsible for the change in diatom community structure is attributed to a change in Si:P ratio produced by leaching of the tephra of Si (Kilham *et al*, 1986), and capping of the sediments by the tephra, thus reducing and recycling of P from the underlying sediments (McBirney, 1968). Additionally, a decrease in light availability is also thought to have been a factor, although the duration of this effect will be limited (Abella, 1988).

Hickman & Reasoner (1994), investigated changes recorded in two alpine to sub-alpine lakes located in British Columbia. Fragilaria species dominate the diatom assemblage in both of these lakes, Opabin Lake and Lake Mary. Within the cores, two tephras were preserved, Mazama and Bridge River tephras, and the impact of these on the diatom community was investigated. The sequence recorded across the tephras preserved in the two of the lakes, record a very similar picture, that of a sharp, dramatic increase in diatom concentration, but no concurrent shift in the composition of the diatom community. While the pattern was replicated between the two lakes, the magnitude of the diatom concentration change was not. One lake (Opabin lake) showed an increase from $<5 \times 10^7$ diatoms/cm^3 to 200×10^7 diatoms/cm^3 immediately after the tephra across the Bridge River tephra and up to 120×10^7 cm^3 after the Mazama tephra. Lake Mary recorded an increase from 20×10^7 diatoms/cm^3 to 40×10^7 diatoms/cm^3 only (Hickman & Reasoner, 1994). Another significant difference between the records preserved in the lakes is that in Lake Mary the change occurring

across the Bridge River tephra was well within the range of changes seen in the core outside of tephra events (Hickman & Reasoner, 1994). The authors postulated that elevated levels of Si leached from the tephras were responsible for the increase in diatom concentration, and the elevated levels of diatoms lasted for several hundred years in both lakes across both tephras, and after this time retuned to pre-tephra levels.

A core extracted from Telegraph Creek, a small sedge marsh high in the Boulder Mountains, Montana, recorded two tephra layers representing the Glacier Peak eruption of 11,200 yr B.P. and the Mount Mazama eruption of 6700 yr B.P. (Brant & Bahls, 1995). Across the younger event, no changes were recorded in the composition of the diatom assemblage inhabiting the lake. However, across the Glacier Peak tephra, preserved as two closely spaced layers of volcanic ash, a significant but short-term change in conditions is recorded within the marsh. The impact of the tephra appears to be very localised, only affecting benthic habitats (Brant & Bahls, 1995). Above the tephra, the diatom *Navicula simplex* becomes prominent for a short time. *N. simplex* is an ecologically anomalous species compared to the dominant taxa in the lake, being a eutrophic, halophilic and alkaliphilous species, and indicates that the input of the tephra had a strong, but local influence on the lake. Across the tephra, planktonic diatoms were unaffected, with *Aulacoseira distans*, the dominant taxa within the lake, remaining unchanged. It is postulated the tephra quickly sunk to the bottom of the marsh, where the highly reactive volcanic particles began dissolving immediately, releasing small amounts of nutrients onto the bottom of the marsh, creating a highly specialised microenvironment. This resulted in this zone becoming enriched in Na, S, N, P, Si and many trace elements, and caused the bottom-waters to become brackish and more alkaline compared to the waters above. This facilitated in the explosion in abundance of *N. simplex*. The influence of the tephra on the marsh was very short, with *N. simplex* dropping to pre-tephra levels after several years.

The largest lake ever investigated for diatom response to tephra input was Lake Tanganyika, in the East African rift valley system (Haberyan, 1998). Lake Tanganyika covers several hundred square kilometres with a maximum depth of 1470 m, contains at least 3 km of sediment, and is approximately 300 km from Mt Rungwe, which is believed to be the source of the tephra preserved in the lake. Modern Lake

Tanganyika is an alkaliphilous, slightly saline lake with low levels of suspended particles in its surficial waters, resulting in the photic zone reaching considerable depths (Haberyan, 1998). The samples investigated were collected from a core recovered from 440 m water depth. In the middle of the 10.6 m core (at 11,850 BP), a 56 mm-thick tephra layer was identified, and samples were extracted from 10 mm below the tephra to 74 mm above, with these samples representing an age spread of 9 years pre-tephra to 68 years post tephra (Fig 3.3).

Lake Tanganyika, East Africa (56 mm thick)

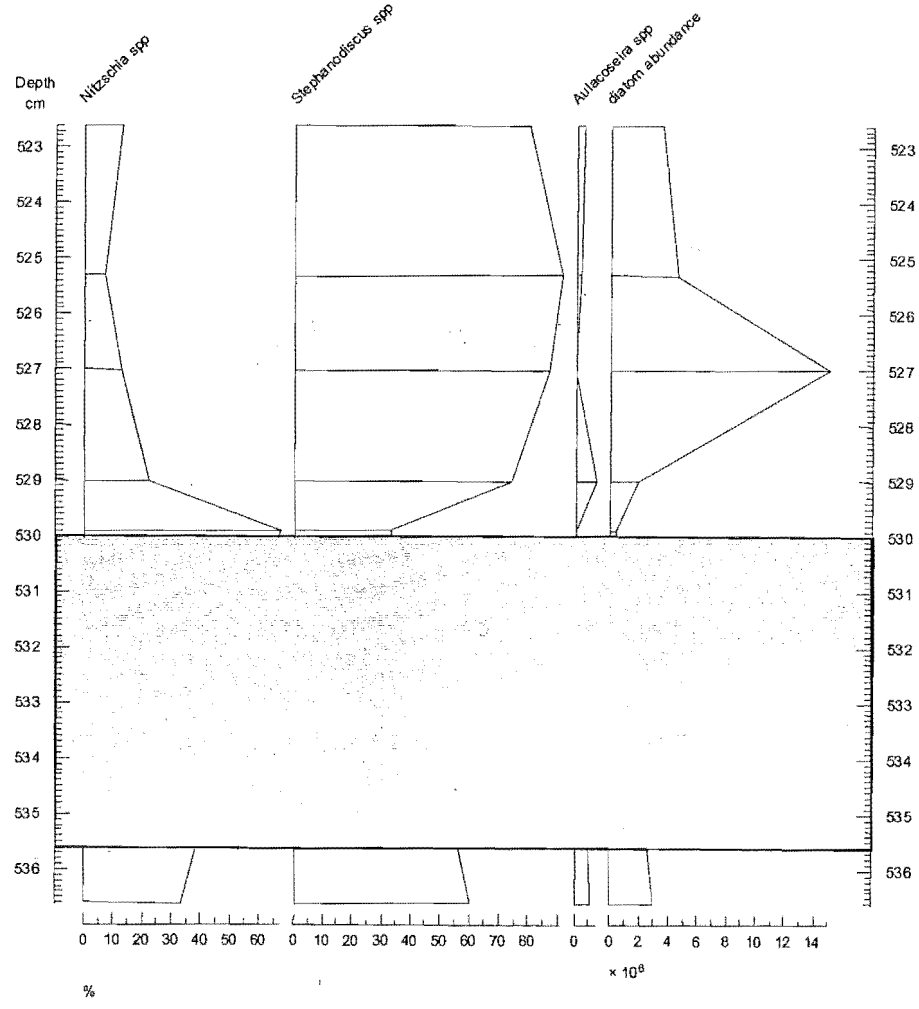


Figure 3.3: Diatom response across tephra from Lake Tanganyika. (Source: redrawn from Haberyan, 1998)

The results show a significant, but short-lived change in both diatom concentration and species composition. The most dominant pre-tephra diatom species (all planktonic forms), *Stephanodiscus* species (*S. astraea* and *S. damasii*), *Nitzschia* spp. and *Aulacoseira granulata* remain prominent post-tephra, but their relative importance shifts in the sample directly above the tephra, with *Nitzschia* replacing

Stephanodiscus as most abundant taxon. Pre-tephra conditions are reinstated in the sample after this and remain constant after this point to the end of the record (Haberyan, 1998). This pattern is repeated with respect to diatom abundance data, which shows a dramatic drop-off in the sample directly above the tephra (e.g. *Nitschia* spp. decreased 75% in the sample immediately above the tephra), but with pre-tephra levels being restored after this. Haberyan (1998) believes that the sudden, but short-lived species composition change was produced by the settling tephra making the normally transparent surface waters turbid, thus cutting the depth of penetration of the photic zone. Once the tephra had settled through the photic zone, pre-tephra conditions returned and the dominance of *Stephanodiscus* spp. was restored. The switch in diatom composition was said to have been the result of the tephra being deposited in the lake during the calm season, when turbulence was at a level which could not support a high population of *Aulacoseira* spp. (Haberyan, 1998). Additonally, the level of Si would have to have been relatively high so *Nitzschia* spp. could outcompete *Stephanodiscus* spp. These conditions were only short-lived, and the diatom community recovered to pre-tephra conditions within a decade (Haberyan, 1998).

3.3 *Smothering Effects of Tephra*

The only study undertaken in New Zealand concerning responses of diatoms to tephra input was conducted in Lake Poukawa (Harper *et al*, 1986). The diatom flora was investigated specifically to assess changes in lake morphology and any effects produced by tephra input. Two tephras were preserved in the cores extracted from the lake, with both of these having originated from the Taupo Volcanic Zone, and more specifically, the Taupo caldera. The characteristics of Lake Poukawa are very different to either Lake Pupuke or Pukaki Crater. The most important of these is that Lake Poukawa is less than 1 m deep compared to ~55 m for Lake Pupuke, and also considerably less than the inferred depth of paleolake Pukaki.

Samples taken across the tephras preserved in the sediment (Taupo and Waimihia tephras) show a considerable increase in diatom concentration in samples above the ash layers (Fig. 3.4) (Harper *et al*, 1986). Diatoms inhabiting planktonic and epepelic environments responded immediately to the ash input, with their numbers increasingly

several orders of magnitude, whereas epiphytic species were much slower to respond. Not only did epiphytic species not respond as quickly, but the response of these species was also muted compared to that of planktonic and epipelic species. Harper *et al* (1986) postulated that this indicated that their habitat was partly destroyed by the tephra with the settling pumices becoming trapped in the plants, therefore shading the diatoms living on the plants. By the time the effect on their habitat had diminished, the nutrients deposited in the lake from the tephra would have dissipated. The elevated levels of diatoms in Lake Poukawa after the Waimihia tephra lasted approximately 300 years, although it was not apparent whether this was related solely to the tephra input, as the lake appeared to have expanded following the tephra (Harper *et al*, 1986), possibly by tephra having blocked outflow channels.

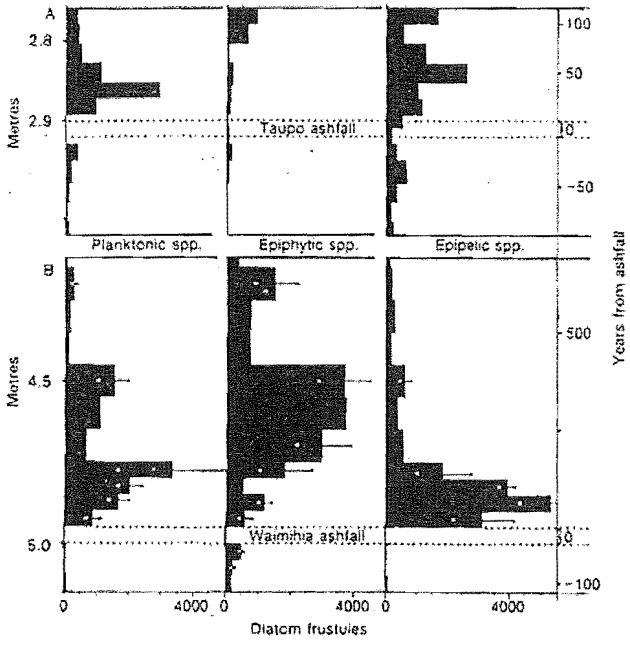


Figure 3.4: Response of different ecological groups to input of Taupo tephra (A), and Waimihia tephra (B) (Source: Harper *et al*, 1986)

Harper *et al* (1986) also demonstrated why epepelic diatoms were not adversely affected by the settling tephra burying their habitats by establishing that epepelic diatoms can successfully move up through 5 cm of fine ash relatively quickly to reach the new sediment-water interface, and therefore the photic zone.

3.4 *Change in pH*

Various sites affected by the Laacher See tephra in Central Europe have been studied for diatom changes (Lotter & Birks, 1993; Birks & Lotter, 1994). They investigated four sites in southern Germany to determine whether the Laacher See tephra had had a statistically significant effect on terrestrial pollen and diatom assemblages. Two of the sites are presently lakes (Rotsee and Holzmaar) (Lotter & Birks, 1993), with the remaining two sites being overgrown lakes, now covered by bogs (Hirschenmoor and Rotmeer) (Lotter & Birks, 1993; Birks & Lotter, 1994). The acidity conditions in the four sites are different, and this appears to control the response of the diatoms to the input of the tephra. The two present-day lake sites are dominated by alkaliphilous taxa (Rotsee) and alkalibiontic taxa (Holzmaar), and in both of these sites, alkaliphilous taxa showed a slight increase across the tephra, for Rotsee at the expense of circumneutral taxa, and at Holzmaar, for alkalibiontic taxa. Although both sites record the same response in terms of pH shift, the species which represent the changes are different, with Rotsee recording an increase in *Achnanthes minutissima*, and Holzmaar represented by increased abundance of *Asterionella formosa* and *Fragilaria brevistriata* (Lotter & Birks, 1993). The two bog-covered sites contain different records to those at the previous two sites. The acidity conditions in Hirshenmoor are similar to the two lake sites, but are more alkali-neutral than Rotsee or Holzmaar. There is no pH change, as well as no change in habitat status recorded across the Laacher See tephra at this locality, and only very small species composition changes – all of which occur within the natural background level of change recorded throughout the core length (Birks & Lotter, 1994). The Rotmeer locality shows the most significant shift in both species composition and inferred-pH conditions of any of the sites Laacher See tephra sites. The major shift in species composition is that of *Aulacoseira valida* and *Aulacoseira alpigena* increasing in abundance at the expense of *Achnanthes minutissima*, *Fragilaria brevistriata* and *Fragilaria construens* v *venter*. This corresponds as an increase in acidophilous taxa. This shift is maintained up until the onset of the major climatic event, the Younger Dryas, 200-300 years after the deposition of the Laacher See tephra, when the species composition undergoes major changes (Lotter & Birks, 1993; Birks & Lotter, 1994).

The statistical methods undertaken by the authors (partial redundancy analysis and associated permutation tests) showed that for all four sites the changes seen could not

be statistically matched solely to the input of the Laacher See Tephra, and that lithology changes may have been the primary factor in producing the changes recorded (Lotter & Birks, 1993; Birks & Lotter, 1994).

3.5 *No impact*

Investigations at two sites, in Ethiopia and British Columbia, indicate that tephra does not always impact on the diatom assemblage, and while changes may be recorded across a tephra bed, the influx of tephra into the lake is not always responsible.

A core recovered from Lake Tilo, Ethiopia, contains as many as 14 tephra beds in a 23.5 m length of core. Diatom analysis across many of these tephras in the 9000 year record shows significant species changes (Telford, 1998; Telford & Lamb, 1999), however, the process which controls diatom responses in Lake Tilo is believed to be changing groundwater conditions (Telford & Lamb, 1999). Changing climatic conditions, which previously had caused little impact on the lake environment, became a major factor once groundwater supply decreased shortly after one of the tephras. While in many instances, tephra do occur coincidentally with changes in the diatom composition, it is believed that they did not play a significant role in determining the taxa inhabiting the lake either within the section as a whole, or specifically, across the tephra beds. Distinguishing between the impact of tephra deposition and other variables, in this case changing lake pH, however, is problematic (Telford, 1998), which is not uncommon (e.g. Lotter & Birks, 1993; Birks & Lotter, 1994).

In another study, Hickman & Reasoner (1998) repeated their investigation of the impact of the Mazama and Bride River tephras on alpine to sub-alpine lakes in British Columbia. However, in this study, tephra is believed to have had no impact on the diatom assemblage. The study site, Crawfoot Lake, records a different picture to that preserved in Opabin Lake and Lake Mary (1994). Diatom concentration does increase across the Mazama tephra, increasing from $<100 \times 10^6$ diatoms/cm^3 to 400×10^6 diatoms/cm^3, however, based on the timing and duration of the change (4500 years), Hickman & Reasoner (1998) concluded that the increase is not a response to the tephra input, instead was caused by vegetation and climatic changes (Fig. 3.5).

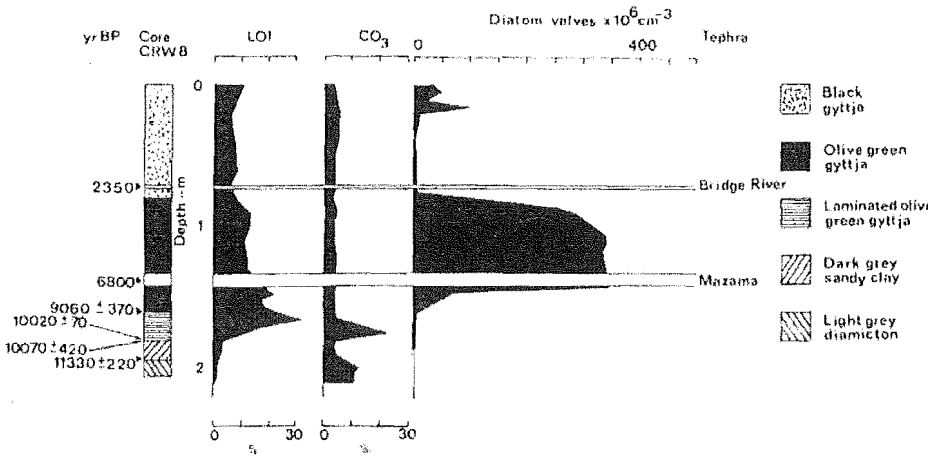


Figure 3.5: Records of loss-on-ignition, carbonates and diatom concentrations (Source: Hickman & Reasoner, 1998).

Chapter four:
Study Sites and Methods

4.1 *Study Sites*

In this section, I will outline the two sites from which samples were collected, Lake Pupuke and Pukaki Crater, describing their respective histories, with the aim of producing a picture of what these sites constituted at the time of the influx of the tephras.

4.1.1 Lake Pupuke

Lake Pupuke (36°47.25'S, 175°46.25'E) is a small, deep freshwater lake situated on the North Shore of Auckland, New Zealand (Fig. 4.1). It is located within a volcanic crater formed by a maar-style eruption, which has since filled up with freshwater, forming the present-day lake. The eruption which formed Lake Pupuke occurred at 140,000 (±10) ka (Wood, 1991), and was one of the first sites of activity within the Auckland Volcanic Field (Allen *et al*, 1996).

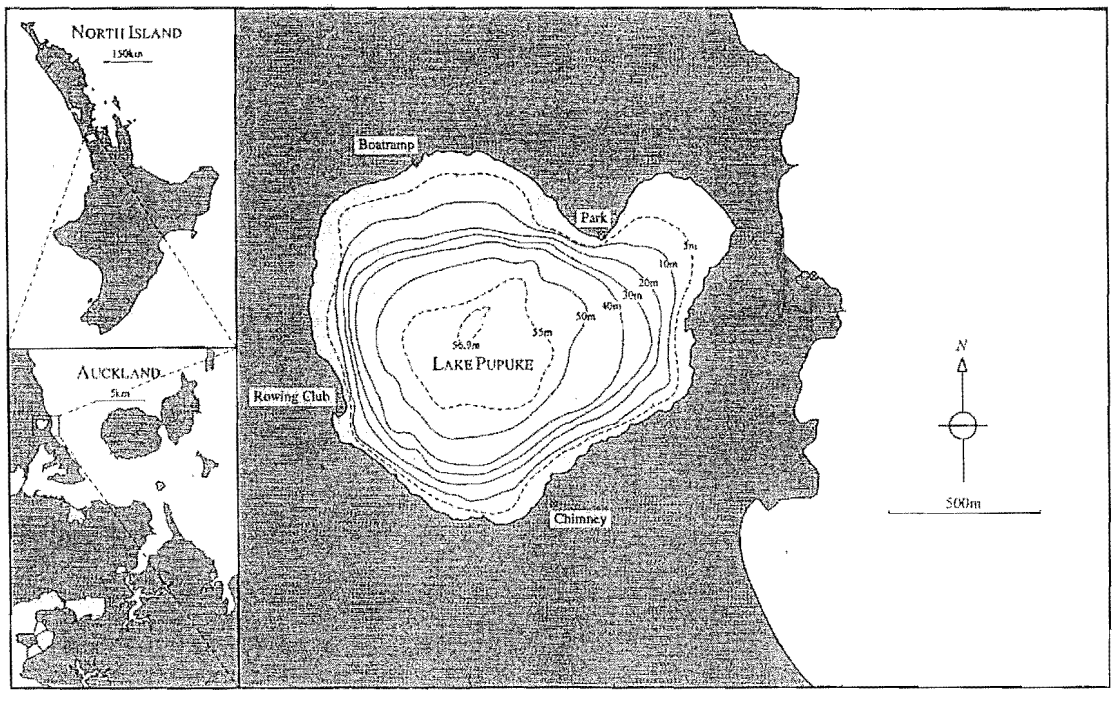


Figure 4.1: Location map of Lake Pupuke showing depth contours (Source: Holmes, 1994)

The eruption which formed Lake Pupuke produced 0.45 km^3 (DRE) of ejecta material, and excavated a crater 1.1 km^2 in area (Allen *et al*, 1996). 140,000 years ago, the site was situated 40 m above sea level (Allen, 1992), and underlain by approximately three metres of water saturated Plio-Pleistocene clays and silts at or near the ancestral Wairau river (Searle, 1964; Rout *et al*, 1993). The eruption of Lake Pupuke occurred in five distinct stages (Allen *et al*, 1996):

1. Magma rose up into the water-saturated sediments producing phreatomagmatic activity which cleared the vent area of this saturated material. Large quantities of country rock-dominated material were ejected in this phase, none of which remain exposed.
2. Fire-fountaining with associated lava effusion formed an extensive lava apron extending up to 3 km in diameter and up to 15 m thick.
3. Low-level Strombolian activity limited to the western flanks of the ventral area produced an 8 m thick lapilli which underlies the younger tuff-ring.
4. Major activity centred within present-day Lake Pupuke produced the extensive tuff-ring deposits which currently surround the lake.
5. The final phase of activity was marked by additional sporadic, localised and smaller-scale tuff-ring eruptions from multiple vents located generally to the south and west within the now-extensive crater.

4.1.1.1 Physiology

The lake has a maximum depth of 56.9 m (Fig 4.1), which occurs roughly at its centre (Main & Barnes, 1989). While the lake is small, with a surface area of only 1.10 km^2, its catchment is even smaller, at 0.80 km^2. This is because the catchment is restricted to the inner slopes of the tuff ring (Fig. 4.2) (Büchel, 1993). Because of this, the majority of water entering Lake Pupuke is from rainfall directly into the lake, with an average of 1.3 x $10^6 m^3$ of rainfall falling directly into the lake each year (Reid, 1979). As no major streams flow into the lake, the only source of water from the catchment is through runoff. No figures are available for calculated levels of runoff in the geologic past, but present day stormwater flow averages 0.5 x 10^6 m^3 per year (Reid, 1979). These levels will be approximately the same; well within an order of magnitude, and the only major difference will be associated with the length of time it takes for the runoff to reach the lake.

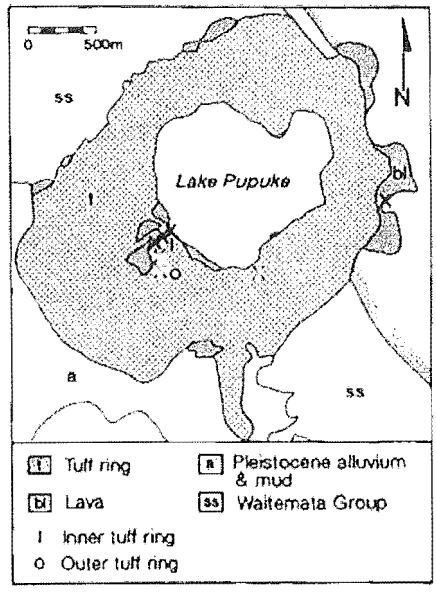


Figure 4.2: Geologic map of Lake Pupuke (Source: Allen *et al*, 1994)

Lake Pupuke is a circular lake, which is common for volcanic-derived lakes (Irwin, 1975). The bathymetry of the lake shows it as having steep sides and a relatively flat bottom (Fig 4.1). This geometry is characteristic of maar lakes which is a major reason for why maar lakes are ideal sites for the investigation of paleoclimates. The sedimentation conditions that prevail in a deep, steep sided lake are conducive to the preservation of cohesive, complete records because:

a) Wave-driven currents will not occur at the bottom of the lake due to the depth, and this will mean that the sediment is not disturbed once it has been deposited. The flat-bottomed geometry of the lake will also influence this. However, density and geostrophoic currents are possible on the lake bottom, though the influence of these is likely minor.

b) As Lake Pupuke is not a particularly deep lake, once the sediment passes through the depth which currents and turbulence persist, the material will descend directly to the bottom of the lake and not remain in suspension for an extended period of time.

c) Because the sides of the lake are steep, sediment does not accumulate and result in mass flows surging onto the lake bottom. Mass movement of sediment can have a significant effect on the deposits preserved in a lake.

The post-eruptive evolution of maar lakes is well understood (Fig 4.3) (Büchel, 1993). This progresses from an empty crater immediately after the initial maar

eruption (A), through the creation of a maar lake (B), to the formation of an infilled crater (C) and finally to a post-sedimentary erosion phase where the crater sediments have been eroded to leave the diatreme exposed (D). Lake Pupuke is currently in stage B. There is no time scale associated with each stage in the evolutionary cycle because the duration of each stage is entirely dependant on local environmental and climatic conditions present at the time.

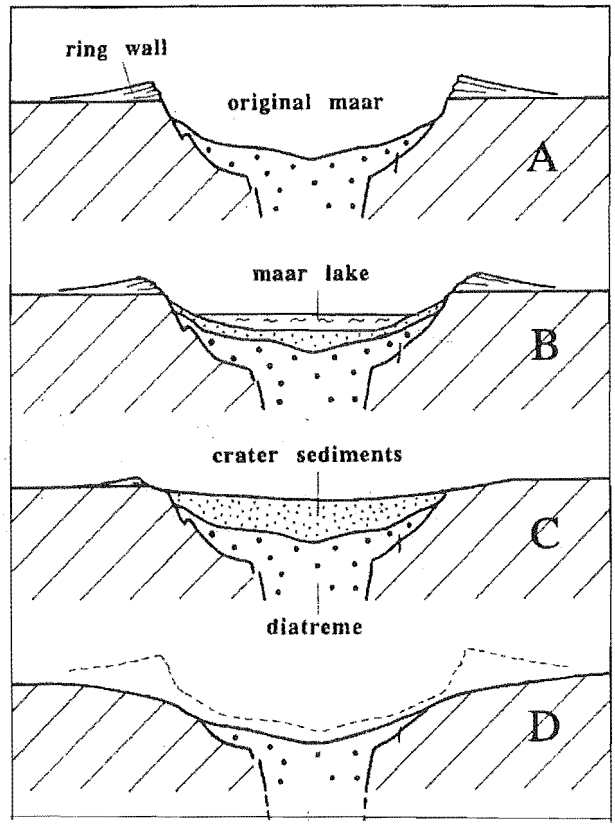


Figure 4.3: Evolution of post-eruption maar craters (Source: Buchel, 1993)

The eastern side of the lake is situated within 200 m of the coast (Searle, 1981). This side of the catchment is constructed of basaltic lava flows, which has effectively formed a barrier between the lake and the sea, and prevented erosion and subsequent incursion into the lake by the sea (Holmes, 1994). Invasion of the sea into maar lakes has occurred in many of the maar-eruption crater lakes within the Auckland region (e.g. Onepoto Crater, Panmure Basin, Tank Farm and Pukaki Crater). As well as protecting Lake Pupuke from the sea, the barrier along the eastern flank of the lake also results in there being no surface outflow from the lake. While surface outflow does not occur, water does escape through numerous fissures and cracks in the surrounding basalt. The largest of these subterranean outflow systems emerges on a coastal basalt platform at Thorne Bay Springs, 200 m from the closest point of Lake

Pupuke (Holmes, 1994). The amount of water flowing out will remain constant because it is controlled by the dimensions of the cracks and fissures, and will not increase considerably during times of high rainfall (Hoare & Spigel, 1987). Therefore, the dominant control on water level is the amount of precipitation falling within the catchment, but as the catchment is small, changes in lake level will be minimal (Reid, 1979).

Lake Pupuke is currently mesotrophic, though as recently as 1967 it was eutrophic (Barker, 1967; Green, 1975; Reid, 1979; Holmes, 1994), with a pH of between 7.25 and 8.6 (Hägg, 2002). The major limiting nutrient on phytoplankton is phosphorus, though the role of silica in the lake has not been investigated (Holmes, 1994). Interestingly, the amount of P leaving the lake through outflow and by deposition of sediments within the lake was calculated to be higher than the influx of P from rainfall and runoff (Fig. 4.4) (Vant & Pridmore, 1990; Holmes, 1994). The implications resulting from this are unclear, although influx of P from recycling of sediments deposited within the lake (see section 2.4.1.2) is not taken into account, and this may explain the difference in influx and efflux values calculated. At a depth of 45 m, present-day Lake Pupuke is thermally stable (oligomictic), and displays depleted oxygen levels: ~4 mgL^{-1} in summer, which is almost completely anoxic, and ~7.8 mgL^{-1} in winter (Holmes, 1994).

The depth to which water is mixed within the water column specifically influences diatoms through turbidity and turbulence, and as discussed in chapter 2, this can have a significant effect on the structure of a diatom community. Additionally, the depth to which light penetrates into the water column, and therefore the depth of the photic zone, is also influenced by the mixing depth of lakes. In this regard, light penetration in Lake Pupuke is low, with a Secchi depth of 2.2 m (Green, 1975). This is because the lake is productive and has a high percentage of suspended particles and phytoplanktonic organisms which block the path of the light down through the water column (Green, 1975). Importantly, the light penetration directly after an influx of tephra will be even lower, with the added input of tephra particles increasing turbidity.

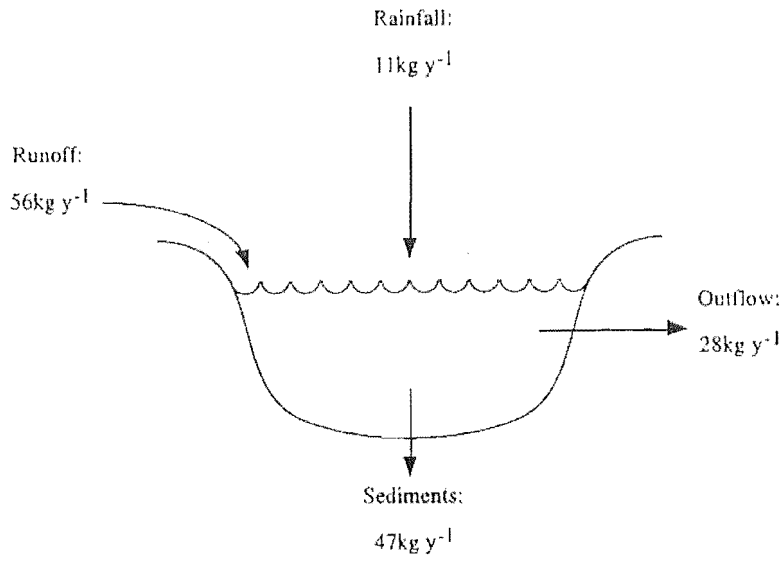


Figure 4.4: Major fluxes of phosphorus from Lake Pupuke. (Source: Holmes (1994))

The mixing depth of Lake Pupuke, both in terms of absolute, and relative depths (Davies-Colley, 1988; Holmes, 1994), is high compared to other New Zealand lakes, which in turn have very high mixing depths compared to similar temperate lakes in the Northern Hemisphere (e.g., Green *et al*, 1987). The average mixing depth of lakes in New Zealand is ~7.8 m, whereas it is ~11.5 m at Lake Pupuke (Holmes, 1994). Mixing depth is controlled by a combination of the wind conditions which occur at the lake (wind speed, wind duration and wind direction) (Hutchinson, 1957), fetch, and the depth of the lake. The topography surrounding Lake Pupuke is low; the tuff ring wall only reaches a maximum 30 m in height, which results in the lake receiving proportionally more wind than a lake which is sheltered from the prevailing winds, either by a physical barrier, or through high level vegetation. Additionally, New Zealand receives more wind that other parts of the world because of our marine-dominated environment (Rhoades *et al*, 2002); so this combined with the factors outlined previously produced a high mixing depth in Lake Pupuke (Holmes, 1994).

4.1.2 Pukaki Crater

Pukaki Crater is located in Mangere, South Auckland, approximately 20 km south of Lake Pupuke. The crater is virtually circular and covers an area of 1.76 km^2 and the surface of the crater presently stands at 3.671 m above sea level (Fig. 4.5). Pukaki Crater was initially a maar lake, formed by a phreatomagmatic explosion produced by

the rising magma reacting with groundwater. The initial evolution of Pukaki Crater is comparable to that of Lake Pupuke. The two sites diverged when Pukaki Crater became breached by the sea approximately 7600 years ago and filled in rapidly with estuarine sediment (Coomber, 1998).

Figure 4.5: Pukaki Crater

Pukaki Crater has progressed to late stage C in terms of the evolutionary cycle of post-eruption maar craters as described by Büchel (1993) (Fig. 4.3). The more rapid evolution of Pukaki compared to Pupuke was facilitated by the breaching of its crater wall during rising sea-level. Before the tuff ring was breached by what is now Waiokauri Creek, the lake accumulated 24.8 m of lacustrine sediments. At this time, a large section of the southern rim collapsed, leaving a 20 m wide opening in the tuff ring wall accessible to high tides from nearby Manukau Harbour (Coomber, 1998). Under a terrestrial sedimentation regime, 24.8 m of material was deposited in approximately 98,000 years, at an average sedimentation rate of 0.25 mm/yr. Under estuarine conditions, 44.4 m of marine sediments were deposited in approximately 1000 years at a sedimentation rate of 4.4 cm/yr. The crater filled up with sediment completely by approximately 6,600 years ago. At this time, the Manukau Harbour ceased regularly flooding the crater floor during high tide events, and since then, a 60 cm top soil layer has formed (Coomber, 1998).

Pukaki Crater is believed to have formed at approximately 124.6 ± 15.8 ka. This is based on luminescence dating of ejecta deposits preserved at a depth of 81.18 – 81.32 m (Reiser, 2001). This is in agreement with a previous estimate of the age at less than 120,000 ka, based on sea-level data (Coomber, 1998). However, it is substantially older than tephrostratigraphic data which indicated it was younger than Wiri Mountain volcano at c. 28,000 ^{14}C yr (Sandiford *et al*, 2001).

The maar-style eruption which formed Pukaki Crater produced 19 x 10^6 m^3 of eruptive tuff and ash material (Allen & Smith, 1994), which accumulated around the volcanic crater forming a tuff ring up to 30 m in height (Coomber, 1998). Early investigations using geophysical methods indicated Pukaki Crater as a shallow, dish-shaped crater up to 25 m deep (Rout *et al*, 1993). This in now known to be a severe underestimate, with Pukaki 1-01 reaching well sorted basaltic silts and sands, interpreted as initial maar formation deposits at 73.1 m.

The sediments with which the ascending magma reacted are believed to have been saturated Pliocene-Pleistocene Waitemata Group units. Pliocene-Pleistocene deposits are known to underlie the Auckland region and represent the extensive groundwater reservoir required for the majority of the phreatomagmatic volcanoes which formed in Auckland (Rout *et al*, 1993). Waitemata Group is believed to be involved because deposits within the tuff rim contain fossil mussel clasts which correspond to ejecta debris originating from marine sediments which Waitemata Group sediments represent (Coomber, 1998).

4.2 *Methods*

In this section, the methods followed from the initial core extraction through sample preparation to data analysis will be outlined.

4.2.1 Core recovery

4.2.1.1 Lake Pupuke

The coring operation on Lake Pupuke was conducted on the 17th and 18th December, 2001 using a Mackereth Corer (Mackereth, 1969) by Gillian Turner and Jim Neale,

with assistance from Jamie Shulmeister, Natalie Robinson and Isaac Burwell. All cores were taken in approximately 58.5 m water depth in the central flat bottomed basin of the lake. Six cores were recovered, PUKE1 being 3.2 m long, and PUKE2, 3, 4, 5, 6, all being approximately 6 m in length.

4.2.1.2 Pukaki Crater

Pukaki Crater was drilled during 7-13 February 2001 to a depth of 88.20 m. However, because the last three drilling runs recovered no material, the maximum core length was 85.65 m. The drill rig, a Christainsen 1500 equipped with a 6.5 m mast, was positioned at an elevation of approximately 3 m above sea level. In total, 59 core runs were completed, with an average length of 1.45 m (Shulmeister & Dickinson, 2001).

4.2.2 Core sampling

Because the effect of different thickness of tephra as well as the effects of tephras of differing compositions is being investigated, the tephras which were sampled were chosen so that a representative section across both thickness and compositional variables was included. With regard to the Lake Pupuke core, as only 4 tephras are preserved in the core compared to 41 found in the Pukaki Crater core, all were sampled.

4.2.2.1 Lake Pupuke

Once the core lengths had been cut, split and transported to Victoria University, Wellington, a sampling workshop was conducted on January 30, 2002. One cubic centimetre samples were extracted at 10 mm intervals from 50 mm below to 50 mm above each tephra. Additional sampling was done at 20 mm intervals to 90 mm above and below the tephra, with further samples collected up to 260mm above and 150 mm below the tephra horizon where applicable (Table 4.1). The amount of samples collected and the distance above and below the tephra to where samples were collected was controlled by the continuity of the core material. In many places, there were gaps in the core where the core material had been displaced during extraction.

Table 4.1: Sampling regime

Depth down core	Lake Pupuke samples				Pukaki Crater samples				
from tephra	Rotoma	Tahua	Taupo	Rangitoto	P36(T2)	P36(T3)	P36(T4)	P36(T6)	P40(T5)
260-265	+								
220-225	+								
180-185	+								
140-145	+								
120-125			+		+	+	+	+	+
110-115				+					
100-105	+								
90-95			+		+	+	+	+	+
80-85	+			+					
70-75		+	+	+	+	+	+	+	+
60-65	+								
50-55		+	+	+	+	+	+	+	+
40-45	+	+	+	+	+	+	+	+	+
30-35	+	+	+	+	+	+	+	+	+
20-35	+	+	+	+	+	+	+	+	+
10-15	+	+	+	+	+	+	+	+	+
0-5 Above tephra↑	+	+	+	+	+	+	+	+	+
0-5 Below tephra↓	+	+	+	+	+	+	+	+	+
10-15	+	+	+	+	+	+	+	+	+
20-25	+	+	+	+	+	+	+	+	+
30-35		+	+	+	+	+	+	+	+
40-45	+	+	+	+	+	+	+	+	+
50-55			+	+	+	+	+	+	+
60-65	+								
70-75			+		+	+	+	+	+
80-85	+								
90-95				+					
105-110				+					
110-115									
120-125	+								
150-155	+								

Generally, these gaps were very small, and did not affect the sampling interval, but other times the gaps were such that additional sampling could not be conducted. The sampling regime across the Rotoma tephra samples was the most comprehensive (Table 4.1); from 150 mm below to 260 mm above. This is because core surrounding the tephra was intact. On the other hand, around the Tahua tephra, which represents the shortest length of sample coverage, the core had multiple breakages, and this made it very difficult to take additional samples because of the offset between subsequent sections of material. All the samples were collected from PUKE3*. In summary, one Okataina Volcanic Centre tephra, one Taupo Volcanic Centre tephra, one Mayor Island Volcanic Centre tephra, and three sourced from the within the Auckland

Volcanic Field were sampled. Compositionally, three rhyolitic and one basaltic tephras were sampled.

4.2.2.2 Pukaki Crater

Samples were collected from the cores extracted from Pukaki Crater on January 30, 2002. Tephrostratigraphic and tephrochronology work had already been completed on the core, so this enabled sections of the core to be chosen knowing what was preserved. Because the core extracted from Pukaki Crater is more structurally cohesive than the Lake Pupuke core, an identical sampling regime was maintained across all tephras sampled (Table 4.1). 1 cm^3 samples were collected at 10 mm intervals from directly below the base of the tephra to 50 mm below the tephra, with an additional sample collected at 70 mm below the base of the tephra. Above the tephra, samples were collected at 10 mm intervals from directly above the top of the tephra to 50 mm above the tephra, with additional samples collected 70, 90 and 120 mm above the tephra. In summary, two Taranaki Volcanic Centre tephra, one Taupo Volcanic Centre tephra, two Auckland Volcanic Field tephras were sampled. Compositionally, two andesitic, one rhyolitic and two basaltic tephras were sampled.

4.2.3 Sample Preparation

The preparation of the samples recovered from the core followed the procedure modified from those described by Margaret Harper (pers. comm., 2002). These are outlined below.

1) **Drying and Weighing**

   Extract the 'wet' core material from the sample bags, weigh, and then dry by a combination of leaving at room temperature overnight and in an oven set at 50°C during the day. This process usually took approximately 1 week. The dry core material is then weighed and placed in glass beakers.

2) **Oxidation of organic matter**

   Add a few drops of Hydrogen peroxide (27% 100 vol.) to sample of dry core material in a glass beaker. Watch the reaction. If excessive, cool:

   a. add some distilled water,
   b. stir to break up foam,
   c. place petri dish under beaker to catch overflow.

Add distilled water until filled up to 10 ml level in 50ml beaker or 20 ml in 100 ml beaker. Continue checking the amount of reaction, and mash with clean glass or plastic rod if the sediment remains lumpy. If the reaction is slight after about 1 hour place the sample in an oven set at 80 °C for 4 hours, remembering to place glass petri dishes under beakers to catch any spillage and protect the oven. Check for amount of reaction every hour and refill with hydrogen peroxide if sample is drying out. More hydrogen peroxide can be added the after 4 hours if visible brown organic matter still present.

3) **Removal of carbonates**

In a fume cupboard, add a few drops of concentrated (36%) hydrochloric acid using a disposable plastic pipette with petri dishes placed under the beakers to collect spillage. Once the reaction has calmed sufficiently add a pipette full of acid and again wait till reaction calmed completely. Then make up to 20 ml mark in a 50 ml beaker, or 40 ml in 100 ml beaker. Gently simmer on hot plate for 1 hour.

4) **Washing**

Add distilled water until the beaker is nearly full, then remove it from the hot plate and leave uncovered for at least 8 hours. After this time pour off the yellow liquid, watching carefully so no sediment is lost (alternatively you can siphon off from above level sediment.) Keep the first wash in fume cupboard and pour the yellow liquid down the drain in corner of the cupboard with plenty of water. Continue rinsing by placing sediment fraction in plastic centrifuge tubes and fill with distilled water. Place tubes in centrifuge and spin at 3000 revolutions per minute for 8 min. Take out sample tubes and pour off liquid and refill with distilled water. Then place the tubes back in the centrifuge and repeat spin. Repeat 4 times. Check pH is no longer acid with blue indicator paper. If paper shows sample still acidic, repeat process until paper stays blue.

5) **Addition of lycopodium spores**

Add a single lycopodium spore tablet to each test tube. Leave for 30 minutes. Shake the samples for several minutes, making sure that the tablet has completely dissolved. A small amount of froth is likely to form, stir this into the tube by gently shaking the tube. Insert the tubes into the centrifuge and spin as for stage 4.

6) **Removal of sand and tephra**

Remove centrifuge tubes from machine, decant off the liquid, and refill 2/3 with distilled water. Prepare a second set of centrifuge tubes, and label them so each sample number has two tubes, one fill with the sample, and the other clean. Shake each sample for nearly quarter of a minute till no sediment is adhering to the base of the test tube and no "slug" of clay is visible within the tube. Leave for three quarters of a minute and then decant into prepared tube. Keep the suspension in the clean test tube as this is the diatom rich part. Wash the sand and any tephra out of original tube with distilled water and repeat process to return sample to original tube. The tube is then filled up to the 6 ml mark for mounting and storage.

7) **Mounting of diatoms**

Place the coverslips on the edge of hotplate. Shake centrifuge tube and using a small plastic pipette extract a very small amount of material (< 0.5 ml) from the centre of the test tube onto the overturned coverslip. Move coverslips to centre of hotplate and leave to dry. Label slides and put a largish drop of naphrax mount (1.74 R.I.) on the top side. When the coverslip dries, remove it from the hotplate and invert slide onto naphrax mount. Heat the slide. The naphrax will bubble, but do not allow it to bubble vigorously. Once the bubbling has died down, remove from the hotplate and press the coverslip down into the naphrax with a toothpick. Once the slide has cooled, it is ready for microscope work.

4.2.4 Diatom identification and counting

The identification and counting of the prepared slides was conducted on a Zeiss Phomic III, housed in the Geology Department, University of Canterbury, Christchurch at 800x magnification. Diatom identification were principally identified using floras from Krammer & Lange-Bertalot (1986; 1988; 1991a; 1991b), with additional identifications from Patrick & Reimer, 1969; Foged, 1979; Cassie, 1989; Sonneman *et al*, 1999. It was planned to count 400 individual diatom frustules on each slide, as Battarbee (1986) describes this as the optimum number to deliver an accurate sample population.

Lycopodium spore tablets were added at stage 5 as a method of obtaining a quantitative count of diatoms within each slide. Each tablet contains 10679 ± 192 individual spores (Berglund & Persson, 1999), and the occurrences of the individual spores are counted along with the diatoms in each slide. Because the number of individual lycopodium spores contained within each sample is known, by comparing the number of diatoms counted to the number of lycopodium spores counted per slide, a quantitative figure can be obtained which should represent the number of diatoms present within the entire sample. This can then be used to determine diatom concentrations at each level within the core.

4.2.5 Data analysis

4.2.5.1 Autecological indicators

The physiological optimum and range of tolerance for many common species of diatoms with regard to various nutrients, levels of organic enrichment, salinity, pH, and other water-quality conditions has been extensively studied (e.g. Lowe 1974; Van Dam *et al*, 1994). By analysing diatom assemblages in terms of autecological indicators, changes in environmental conditions that occur in lakes can be extracted. The primary method used is comparison to a checklist compiled by Van Dam *et al* (1994). This categorizes individual taxa into groups of similar tolerance for a variety of ecological and environmental variables. In this paper, Van Dam and his colleagues separate 948 taxa, which belong to 776 species and 56 genera, into different categories based on their pH, salinity, nitrogen, oxygen, sabrobity, moisture and trophic status preferences (Table 4.2). The data included is not complete, therefore it was supplemented wherever possible from additional literature (e.g. S. Porter, pers. comm., 2002; R. Telford pers. comm., 2003). With regard to tephra input, not all of the ecological variables are relevant, in particular moisture content and sabrobity, so these indicators are excluded. The categories focused on are pH, N, O and trophic status, as these are the most likely to be either directly or indirectly effected by tephra input (see section 2.4).

Table 4.2: Classification of ecological indicator values (Source: modified from Van Dam *et al*, 1994)

pH		
Acidobiotic	optimal occurance at pH <5.5	
Acidophilous	mainly occuring at pH <7	
Circumneutral	mainly occuring at pH-values about 7	
Alkaliphilous	mainly occuring at pH >7	
Alkalibiontic	exclusively occuring at pH >7	
Indifferent	no apparent optimum	
Salinity	Cl- (mgl-1)	Salinity ‰
Fresh	<100	<0.2
Fresh brackish	<500	<0.9
Brackish fresh	500-1000	0.9-1.8
Brackish	1000-5000	1.8-9.0
Nitrogen Uptake Metabolism		
Lowly nitrogen-autotrophic	tolerates small concentrations of organically bound N	
Highly nitrogen-autotrophic	tolerates elevated levels of OBN	
Mainly nitrogen-heterotrophic	needs periodically elevated levels of OBN	
Only nitrogen-heterotrophic	requires continuously elevated levels of OBN	
Oxygen Requirements		
Continuously high	about 100% saturation	
Fairly high	>75% saturation	
Moderate	>50% saturation	
Low	>30% saturation	
Very low	about 10% saturation	
Trophic Status		
Oligotrophic	requires low nutrient level	
Mesotrophic	requires intermediate nutrient levels	
Eutrophic	requires elevated nutrient levels	
Indifferent	no apparent optimum	

4.2.6 Sediment geochemistry

Nutrients that most affect diatom assemblages are Si, P and N, and of these, Si and P can be significantly altered by the input of tephra into the lacustrine environment (see chapters 2 & 3). Analysis of the sediment surrounding the tephra beds is designed to highlight any changes in the amounts of these nutrients in the water column and therefore available to diatoms following the tephra input. As different species have specific tolerances for these nutrients, any change in the concentration of these nutrients in the water column should be represented in the diatom record (see chapter 2). By analysing the sediments surrounding the tephras, any chemical changes

produced directly or indirectly from the tephra input will be represented in the concentrations of the nutrients within the sediments. Therefore, using XRF analysis undertaken in the Geophysics Lab, University of Canterbury, 15 samples collected across 3 sections were analysed using whole-rock geochemistry on the following elements: $Si0_2$, P_20_3, Fe_2O_3, Al_2O_3, TiO_2, MnO, MgO, Na_2O and K_2O.

Chapter five:
Diatom Species and Diatom Density data

5.1 *Diatom Species data*

In this chapter, the results from the diatom identification and counting procedure are presented, as well as the diatom concentration data. It is divided into 2 sections, comprising the results from a) the Lake Pupuke core and b) the Pukaki Crater core.

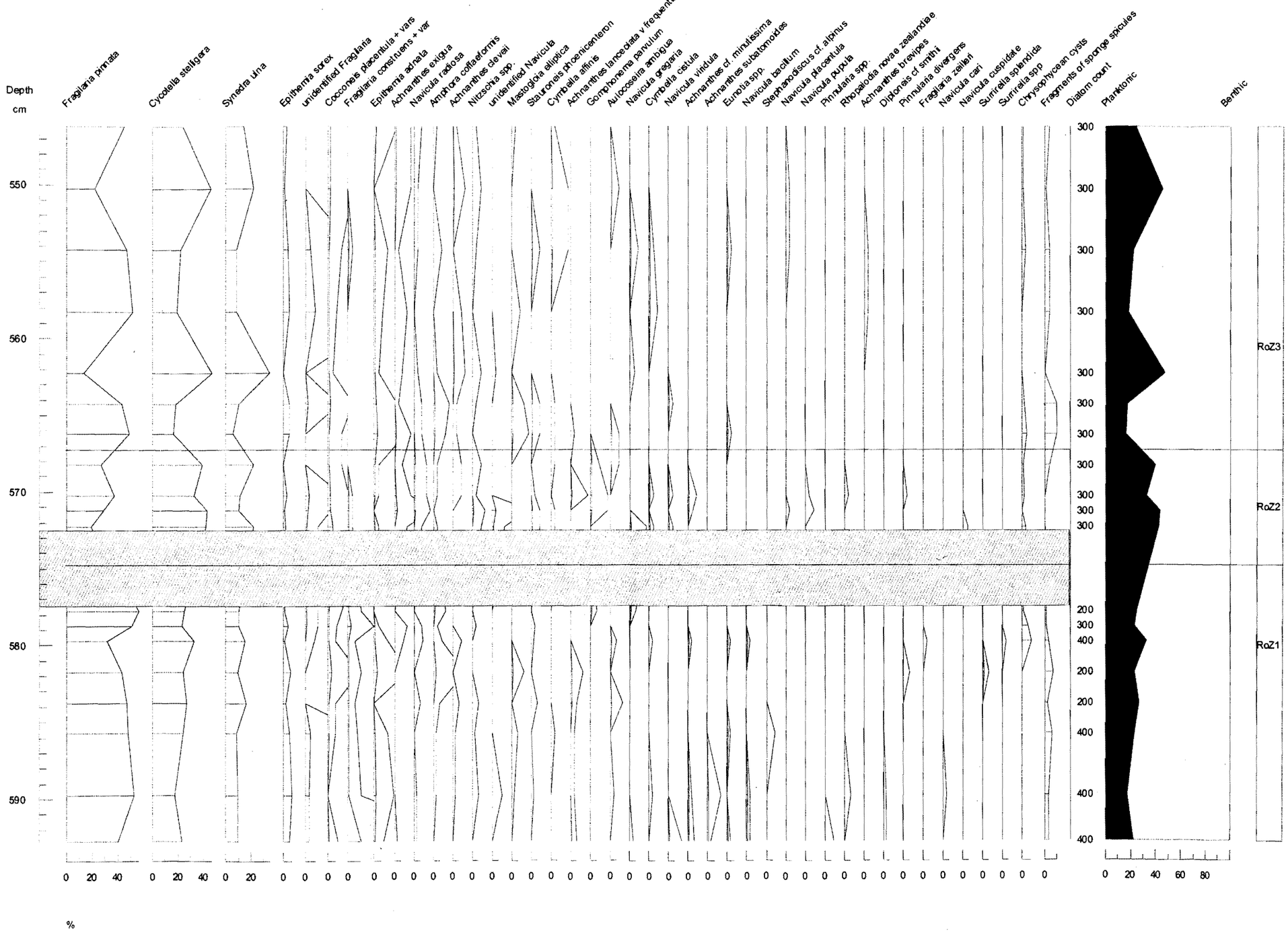
5.1.1 Lake Pupuke Core

5.1.1.1 Rotoma tephra (9.5 ka)

In the cores extracted from Lake Pupuke, the rhyolitic Rotoma tephra is found at 572.5 cm, and has a thickness of 50 mm. The sampling regime across the Rotoma tephra was the most comprehensive in this project, consisting of 19 samples from 592.5 cm (15 cm below the tephra) to 546.5 cm (26 cm above the tephra) - a length of 46 cm (Fig. 5.1). The target count was 400 frustules per slide; however, for the majority of samples, 300 diatoms were counted, and at several levels, only 200 were counted due to scarcity of frustules within these sediments.

In all, 41 diatoms species were identified. The majority of these were very rare, with only three species occurring at above 5% of the total count: *Fragilaria pinnata*, *Cyclotella stelligera*, *Synedra ulna*, and 3 more accounting for more than 1%: *Cocconeis placentula*, *Epithemia sorex*, and an unidentified *Fragilaria* species (Fig. 5.2). When looking at the individual depths sampled, 14 additional species comprised more than 1% of the count in at least one sample. These additional taxa were *Achnanthes cleveii*, *Achnanthes exigua*, *Achnanthes subatomoides*, *Amphora coffaeformis*, *Aul4coseira ambigua*, *Cymbella affinis*, *Epithemia adnata*, *Fragilaria construens*, *Gomphonema parvulum*, *Mastogloia elliptica*, *Navicula gregaria*, *Navicula radiosa*, *Navicula viridula* and *Nitzschia* species.

Rotoma tephra - rhyolitic (50 mm thick)


Depth
cm
Fragilaria pinnata
Cyclotella stelligera
Synedra ulna
Epithemia sorex
unidentified Fragilaria
Cocconeis placentula + vars
Fragilaria construens + var
Epithemia adnata
Achnanthes exigua
Navicula radiosa
Amphora coffaeformis
Achnanthes clevei
Nitzschia spp.
unidentified Navicula
Mastogloia elliptica
Staurosirella phoenicenteron
Cymbella affinis
Achnanthes lanceolata v frequentissima
Gomphonema parvulum
Aulacoseira ambigua
Navicula gregaria
Cymbella cistula
Navicula viridula
Achnanthes cf. minutissima
Achnanthes subatomoides
Eunotia spp.
Navicula bacillum
Stephanodiscus cf. alpinus
Navicula placentula
Navicula pupula
Pinnularia spp.
Rhopalodia novae zealandiae
Achnanthes brevipes
Diploneis cf smithii
Pinnularia divergens
Fragilaria zeilleri
Navicula cari
Navicula cuspidate
Surirella splendida
Surirella spp
Chrysophycean cysts
Fragments of sponge spicules
Diatom count
Planktonic
Benthic
550
560
570
580
590
RoZ3
RoZ2
RoZ1
0 20 40 0 20 40 0 20 0 0 0

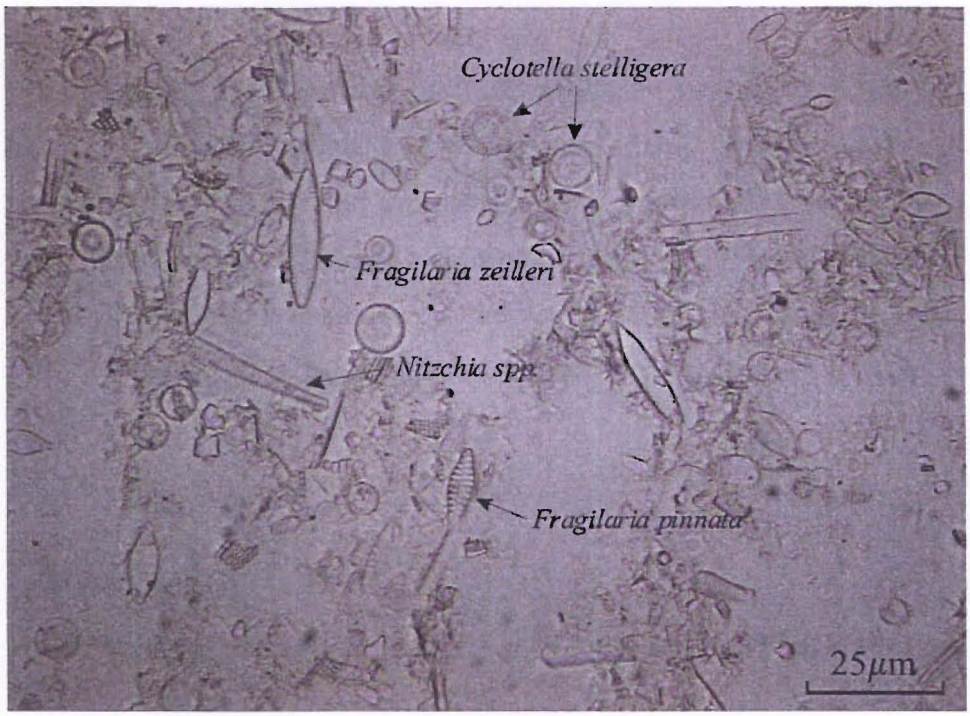


Figure 5.2: Sample view from Rotoma tephra section

Based on changes present in the composition of the diatom, three diatom zones can be discerned (Fig. 5.1).

Rotoma Zone 1 (592.75 cm – 572.50 cm)

RoZ1 encompasses all pre-tephra sediments and the tephra bed itself; from 592.75 cm to 572.4 cm. *F. pinnata* is the dominant species in RoZ1, at 47%, followed by *C. stelligera*, *S. ulna* and *E. sorex* with 24%, 11% and 4% respectively. There are several species which are only present in pre-tephra deposits; these are *Achnanthes subatomoides*, *Stephanodiscus* cf. *alpinus*, *Pinnularia* spp., *Diploneis* cf *smithii*, *Fragilaria zeilleri*, *Navicula cari*, and *Surrirella* spp.

Rotoma Zone 2 (572.50 cm – 567.25 cm)

RoZ2 begins immediately after the tephra (572.4 cm), and stretches 40 mm above the tephra (568.25 cm). It is characterised by *C. stelligera* replacing *Fragilaria pinnata* as the dominant species within the core. *F. pinnata* drops to 28%, whereas *C. stelligera* rises to 39%. Furthermore, *S. ulna* increases to 16.5% and *E. sorex* drops 1.3%. Additionally, there are two taxa which are only present in this zone: *Navicula cuspidata* and *Navicula pupula*.

Rotoma Zone 3 (567.25 cm – 546.25 cm)

F. pinnata replaced *C. stelligera* as the most dominant taxon within the lake. The abundance of *F. pinnata* increased to 39%, whereas *C. stelligera* dropped to 28%. *S. ulna* dropped to 15% and *E. sorex* increases to 3%. Additionally, two diatom species are only present in this zone: *Navicula placentula* and *Achnanthes brevipes*.

Although the relative abundance of the top four species changes between the different diatom zones, the total abundance explained by these taxa remains constant at 86%.

5.1.1.2 Tahua tephra (7.0 ka)

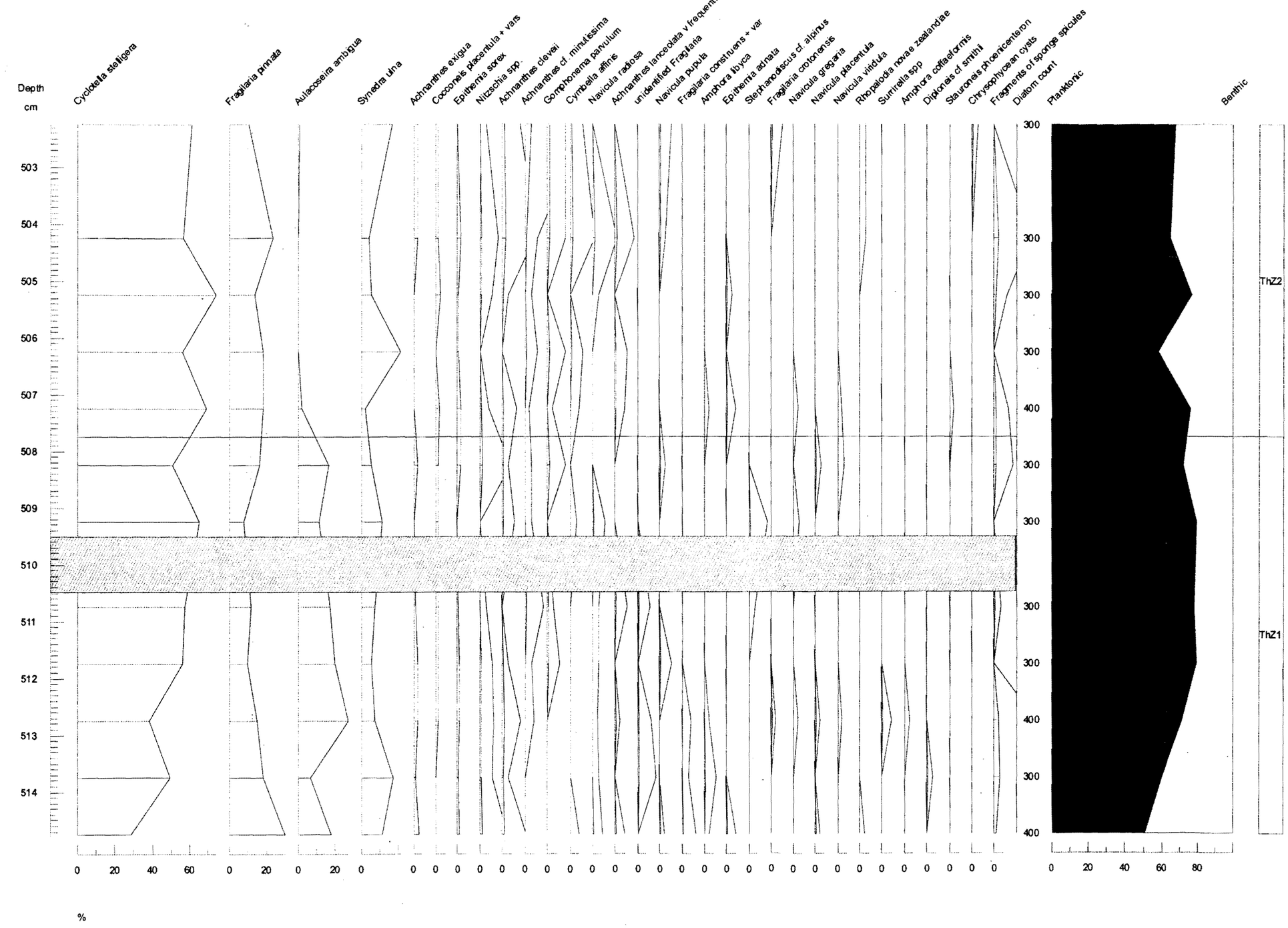
The rhyolitic Tahua tephra is present at a depth of 509.5 cm and has a thickness of 10 mm. Twelve samples were extracted from 514.75 cm (4 cm below the tephra) to 502.25 cm (7 cm above) representing the section length of 12.5 cm (Fig. 5.3). Again, 400 frustules was the target count per slide, but counts of only 300 were achieved in 9 of the 12 samples due low concentrations of diatoms. Twenty-nine diatom species were identified within the section, with the majority of these being very rare. Four taxa comprised more than 5% of the total abundance: *Cyclotella stelligera*, *Fragilaria pinnata*, *Aulacoseira ambigua*, *Synedra ulna*, with two additional taxa accounting for more than 1%: *Achnanthes exigua* and *Cocconeis placentula* (Fig. 5.4). The combined count made up by these species was 87 - 97% per level. On individual levels, 9 additional species comprise more than 1%: *Achnanthes* cf. *minutissima*, *Achnanthes cleveii*, *Cymbella affinis*, *Epithemia sorex*, *Gomphonema parvulum*, *Navicula radiosa*, *Nitzschia* spp, *Stephanodiscus* cf. *alpinus*, and an unidentified *Fragilaria* species.

Based on the composition of the diatom assemblage across the tephra, 2 diatom zones are recognised (Fig 5.3).

Tahua Zone 1 (541.75 cm – 507.75 cm)

ThZ1 extends from the base of the section (541.75 cm) to 1.25 cm above the tephra (507.25 cm). *C. stelligera* is the dominant taxon, accounting for 48% of the diatom count, followed by *A. ambigua*, *F. pinnata* and *S. ulna* with 17%, 16% and 9% respectively.

Tahua tephra - rhyolitic (10 mm thick)


Depth cm
Cyclotella stelligera
Fragilaria pinnata
Aulacoseira ambigua
Synedra ulna
Achnanthes exigua
Cocconeis placentula + vars
Epithemia sorex
Nitzschia spp.
Achnanthes cleveii
Achnanthes cf. minutissima
Gomphonema parvulum
Cymbella affinis
Navicula radiosa
Achnanthes lanceolata v frequentissima
unidentified Fragilaria
Navicula pupula
Fragilaria construens + var
Amphora libyca
Epithemia adnata
Stephanodiscus cf. alpinus
Fragilaria crotonensis
Navicula gregaria
Navicula placentula
Navicula viridula
Rhopalodia novae zealandiae
Surirella spp
Amphora coffaeiformis
Diploneis cf smithii
Stauroneis phoenicenteron
Chrysophycean cysts
Fragments of sponge spicules
Diatom count
Planktonic
Benthic
503
504
505
506
507
508
509
510
511
512
513
514
300
300
300
300
400
300
300
300
400
300
400
ThZ2
ThZ1
0 20 40 60 0 20 0 20 0 0 0

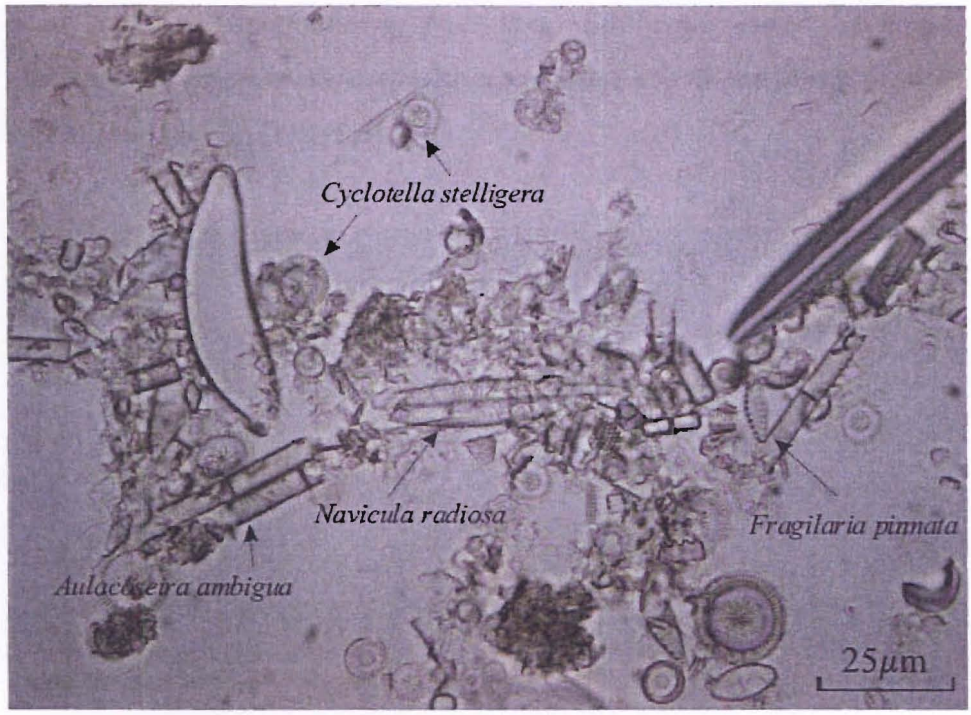


Figure 5.4: Sample view from Tahua tephra section

Tahua Zone 2 (507.75 cm – 502.25 cm)

The onset of ThZ2 is characterized by the sudden decrease and then disappearance of *A. ambigua* from the assemblage. *Fragilaria construens*, *Stephanodiscus* cf. *alpinus*, *Navicula placentula*, *Surrirella* spp., *Amphora coffaeformis* and *Diploneis* cf. *smithii* also disappear at the start of ThZ2. *C. stelligera* is dominant in ThZ2, at 64% of the assemblage, and *F. pinnata* occurs at 16% to 18%.

5.1.1.3 Taupo tephra (1.8 ka)

The rhyolitic Taupo tephra is found 181 cm from the top of the core, and is the thickest tephra recorded in the Lake Pupuke core at 65 mm. 15 samples were collected from 194.75 cm (7.25 cm below), up to 167.75 cm (13.25 cm above) creating a combined section length of 27 cm. The number of diatom frustules counted in each level for the entire length of the section was 400.

32 diatom species were identified across the Taupo tephra, with 4 taxa comprising more than 5% of the count across the section: *Aulacoseira ambigua*, *Cyclotella stelligera*, *Fragilaria pinnata* and *Synedra ulna*. Four additional taxa account for greater than 1%: *Achnanthes subatomoides*, *Cocconeis placentula*, *Fragilaria construens*, and *Nitzschia spp.* Additionally, *Achnanthes cleveii*, *Navicula radiosa*,

Achnanthes exigua, *Gomphonema parvulum*, *Epithemia sorex*, *Achnanthes* cf. *minutissima* and *Epithemia adnata* make up at least 1% of the count in at least one sample within the section (Fig. 5.5).

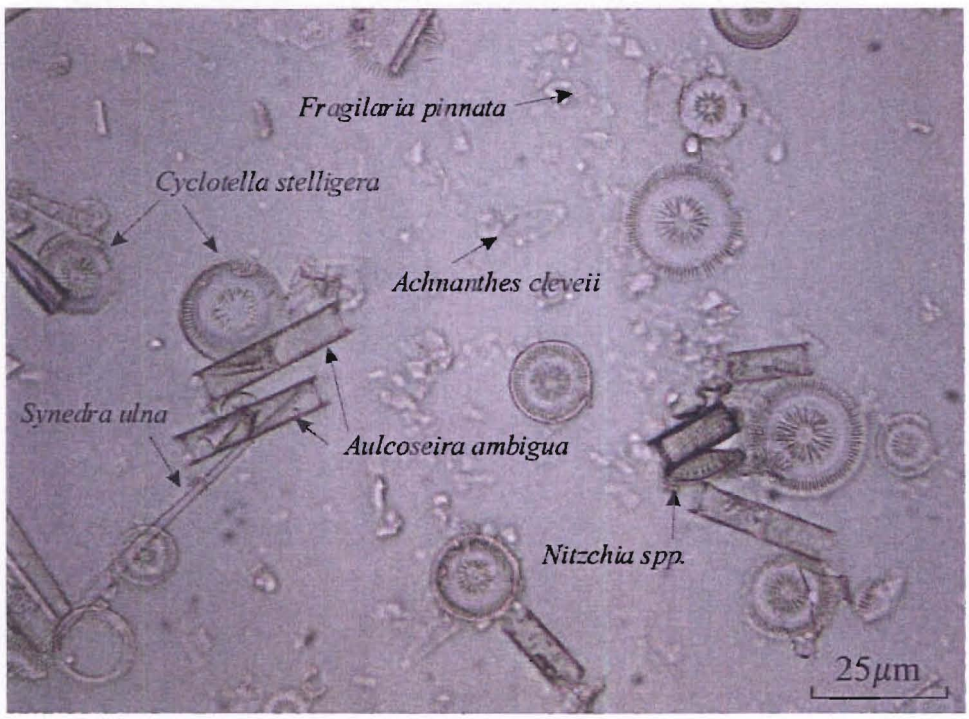


Figure 5.5: Sample view from Taupo tephra section

Based on the diatom assemblage within the section across the Taupo tephra, 4 diatom zones can be created (Fig. 5.6).

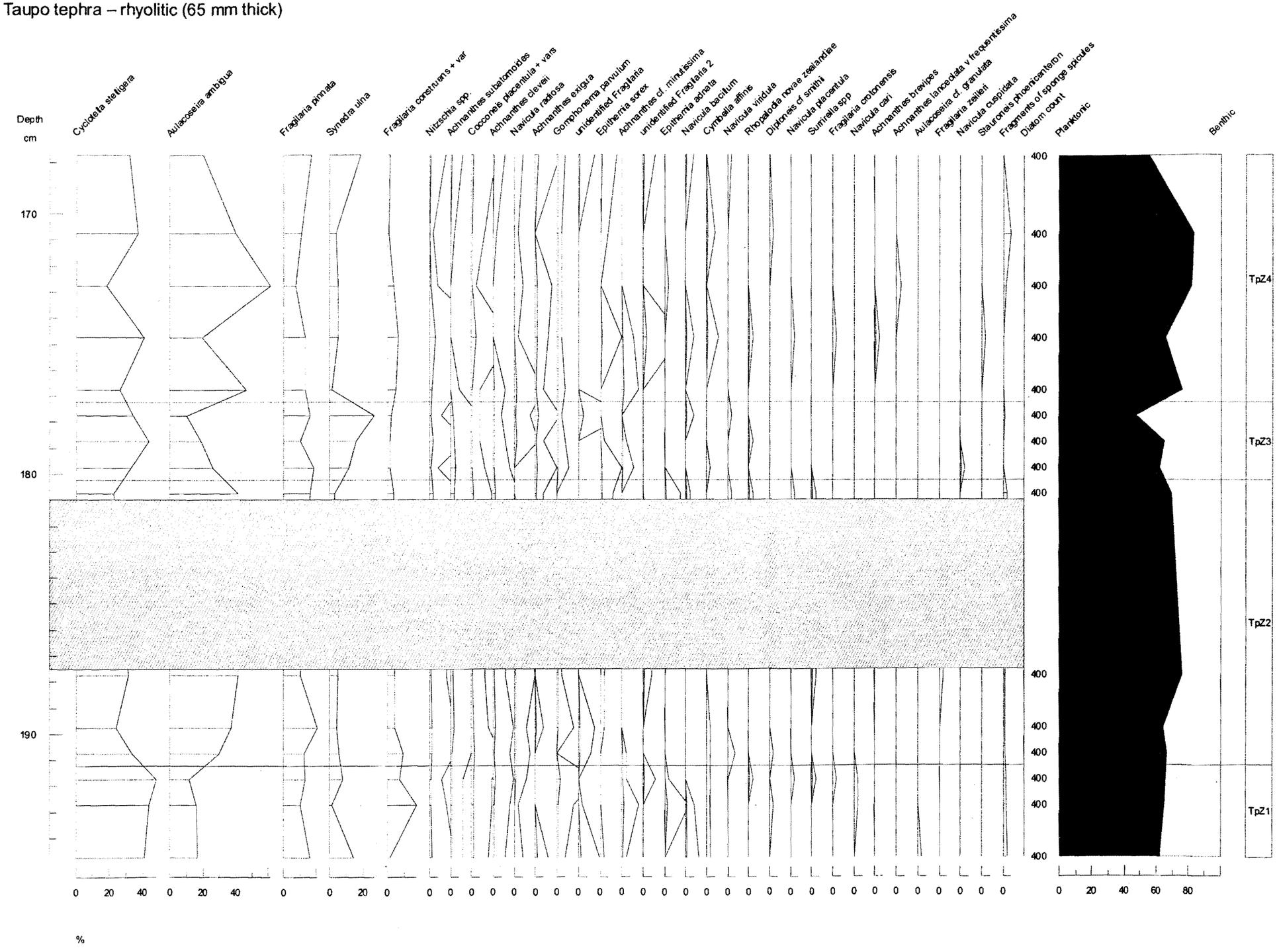
Taupo Zone 1 (194.75 cm – 191.25 cm)

TpZ1 extends from the base of the section, at 194.25 cm to 191.25 cm, 0.75 cm above the top of the tephra. *C. stelligera* is the dominant taxon, at 45%, followed by F. pinnata, *A. ambigua* and *S. ulna* with 20%, 115% and 8% respectively. Two diatom species are only recorded within this zone: *Aulacoseira* cf. *granulata* and *Navicula cari*.

Taupo Zone 2 (191.25 cm – 180.25 cm)

TpZ2 extends from 191.25 cm to 180.25 cm, 0.75 cm above the top of the tephra bed. In this zone, *A. ambigua* is the dominant taxa with 37%, compared with 28% for *C. stelligera*. These are followed by *F. pinnata* and *S. ulna* with 16% and 4% respectively. *Fragilaria zeilleri* is the only taxon restricted to this zone.

Taupo tephra – rhyolitic (65 mm thick)


Depth
cm
Cyclotella stelligera
Aulacoseira ambigua
Fragilaria pinnata
Synedra ulna
Fragilaria construens + var
Nitzschia spp.
Achnanthes subatomoides
Cocconeis placentula + vars
Achnanthes clevei
Navicula radiosa
Achnanthes exigua
Gomphonema parvulum
unidentified Fragilaria
Epithemia sorex
Achnanthes cf. minutissima
unidentified Fragilaria 2
Epithemia adnata
Navicula bacillum
Cymbella affinis
Navicula viridula
Rhopalodia novae zealandiae
Diploneis cf smithii
Navicula placentula
Surirella spp
Fragilaria crotonensis
Navicula cari
Achnanthes brevipes
Achnanthes lanceolata v frequentissima
Aulacoseira cf. granulata
Fragilaria zeilleri
Navicula cuspidata
Stauroneis phoenicenteron
Fragments of sponge spicules
Diatom count
Planktonic
Benthic
170
180
190
TpZ4
TpZ3
TpZ2
TpZ1
400
0 20 40 0 20 40 0 0 20 0 0 0

Taupo Zone 3 (180.25 cm – 177.25 cm)

TpZ3 begins immediately following the first sample above the top of the tephra and stretches for 3.75 cm, to 177.25 cm. In this zone, *C. stelligera* remains the dominant taxon, with 37%, with *A. ambigua* declining and *S. ulna* increasing to become equal with 18%, followed by *F. pinnata*, at 15%. *Fragilaria cuspidata* is the only taxon which is restricted to this zone.

Taupo Zone 4 (177.25 cm – 167.75 cm)

The onset of TpZ4 is characterised by the decline of *S. ulna* to 6%, and the increase of *A. ambigua* to 37%, becoming the dominant taxa within the assemblage. *C. stelligera* drops to 31%, while F. pinnata remains stable at 15%. Three taxa, *Achnanthes brevipes*, *Achnanthes lanceolata* v *frequentissima* and *Stauroneis phoenicenteron* are only recorded within this zone.

5.1.1.4 Rangitoto tephra (0.64 ka)

The basaltic Rangitoto tephra is the youngest of the 4 tephra beds found in the Lake Pupuke core, at 640 years old. The top of the tephra bed is recorded 31 cm from the top of the core and is 25 mm thick. 18 samples were collected within the section, with these spread evenly above and below the tephra. Samples were collected from 44.25 cm (10.75 cm below the tephra) to 19.75 cm (11.25 cm above the tephra), covering a length of 24.5 cm. 46 species were identified in the samples – the most from the Lake Pupuke core. As with the other sections, the majority of these taxa occurred very rarely. Five taxa: *Cyclotella stelligera*, *Aulacoseira ambigua*, *Fragilaria pinnata*, *Stephanodiscus* spp. and *Synedra ulna* achieved values of more than 5%. Four further taxa account for more than 1% of the total count: *Cocconeis placentula*, *Fragilaria crotonensis*, *Navicula radiosa* and an unidentified *Navicula* species. Twelve additional taxa, *Achnanthes cleveii*, *Achnanthes exigua*, *Achnanthes exigua* v *elliptica*, *Achnanthes minutissima*, *Achnanthes subatomoides*, *Epithemia adnata*, *Epithemia sorex*, *Fragilaria capucina* v *vaucheriae*, *Gomphonema parvulum*, *Mastogloia elliptica*, *Navicula cari*, *Navicula radiosa*, *Nitzschia* spp. and *Surrirella* spp. are present in numbers greater than 1% in at least one sample within the section.

Major changes in the composition of the diatom assemblage around this tephra, and three diatom zones have been created (Fig. 5.7).

Rangitoto tephra - basaltic (25mm thick)

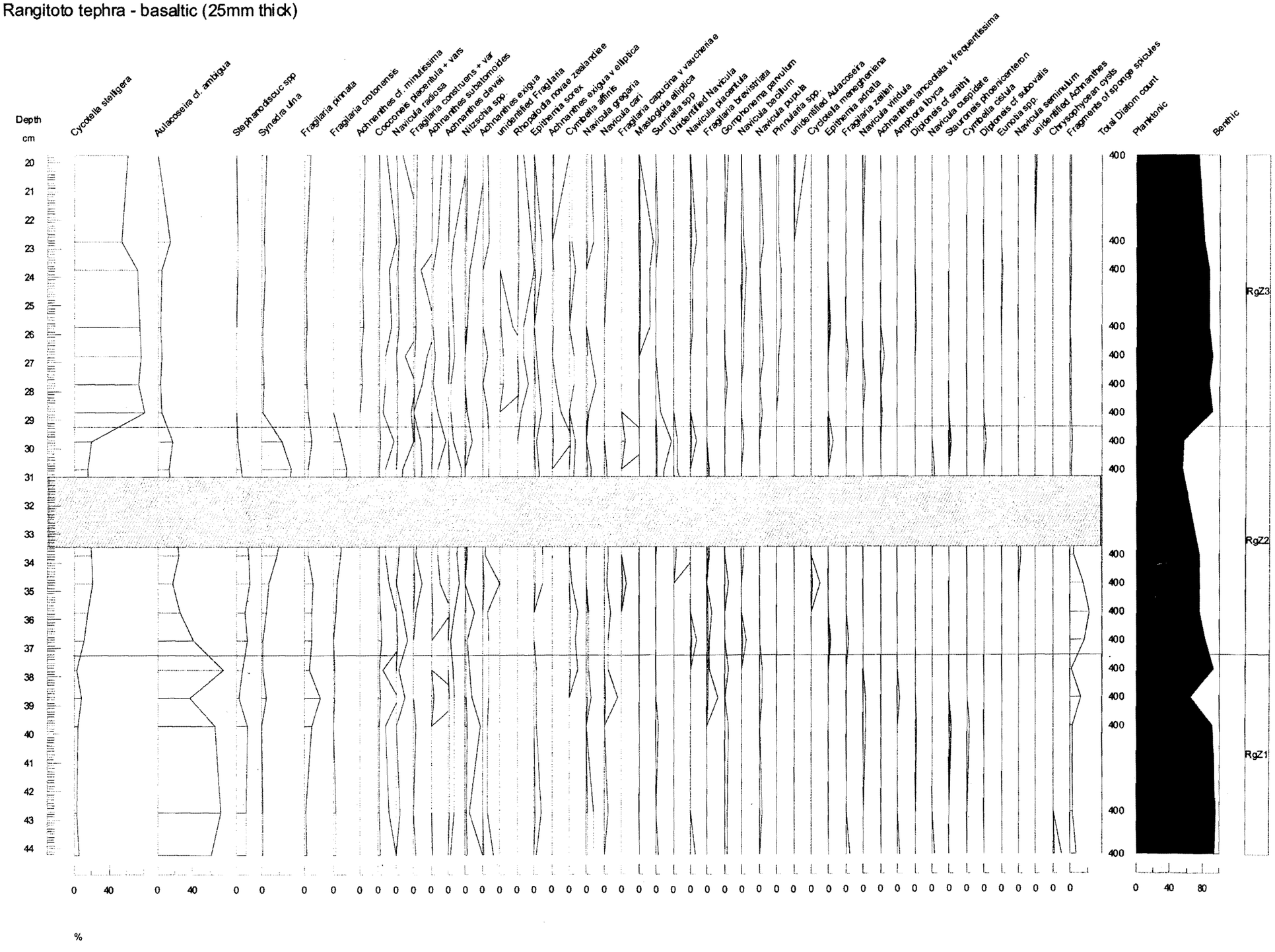


Figure 5.7: Diatom taxa identified across Rangitoto tephra, with x10 exaggeration of taxa <1.4% total count

Rangitoto Zone 1 (44.25 cm – 37.25 cm)

A. ambigua dominates this zone, which extends 6.5 cm from 44.25 to 37.75 cm, with 63% (Fig. 5.8). Other prominent species include *Stephanodiscus* spp., *F. pinnata* and *C. stelligera* with 9%, 7% and 5% respectively. Two taxa are only present in RgZ1: *Amphora libyca* and *Cymbella cistula*. In addition, chrysophycean cysts are only present in this zone.

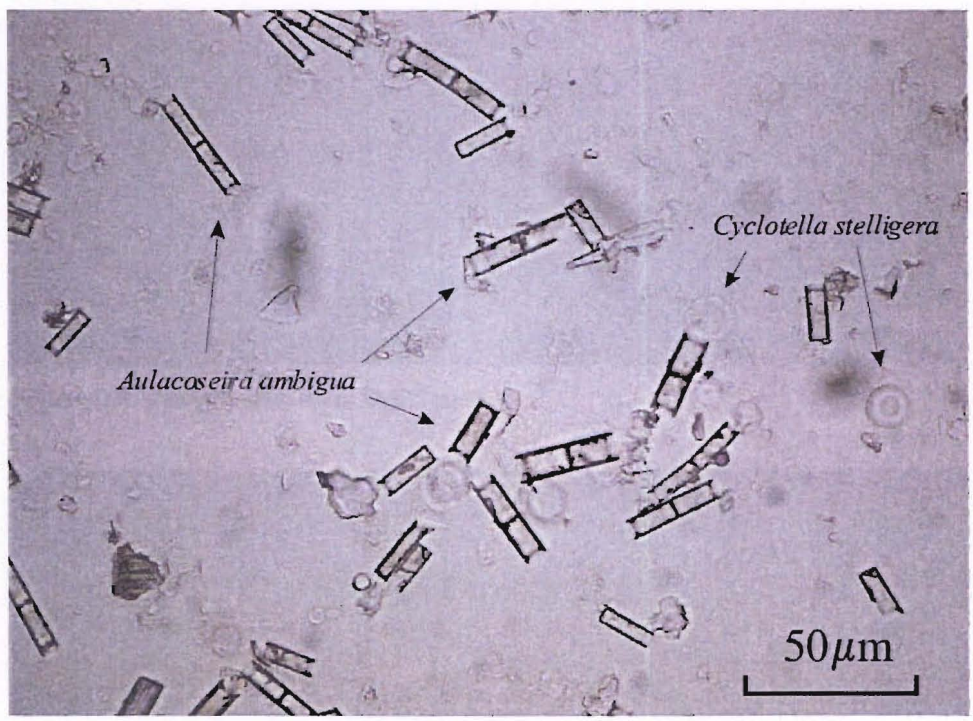


Figure 5.8: Sample view from RgZ1 section

Rangitoto Zone 2 (37.25 cm – 29.25 cm)

RgZ2 stretches for 9 cm from 37.25 cm to 29.25 cm. *A. ambigua* begins to decline at the onset of this zone, dropping to 23%. *C. stelligera, S. ulna* and *F. crotonensis* increase to 17%, 15% and 6% respectively, while *Stephanodiscus* spp., at 10% and *F. pinnata* with 7%, remain unchanged (Fig. 5.9). Sponge spicules increase significantly, especially below the tephra, to average 10%. Four additional taxa, *Fragilaria capucina* v *vaucheriae*, *Cyclotella menegheniana*, *Diploneis* cf. *subovalis* and *Navicula seminulum* are only recorded in this zone.

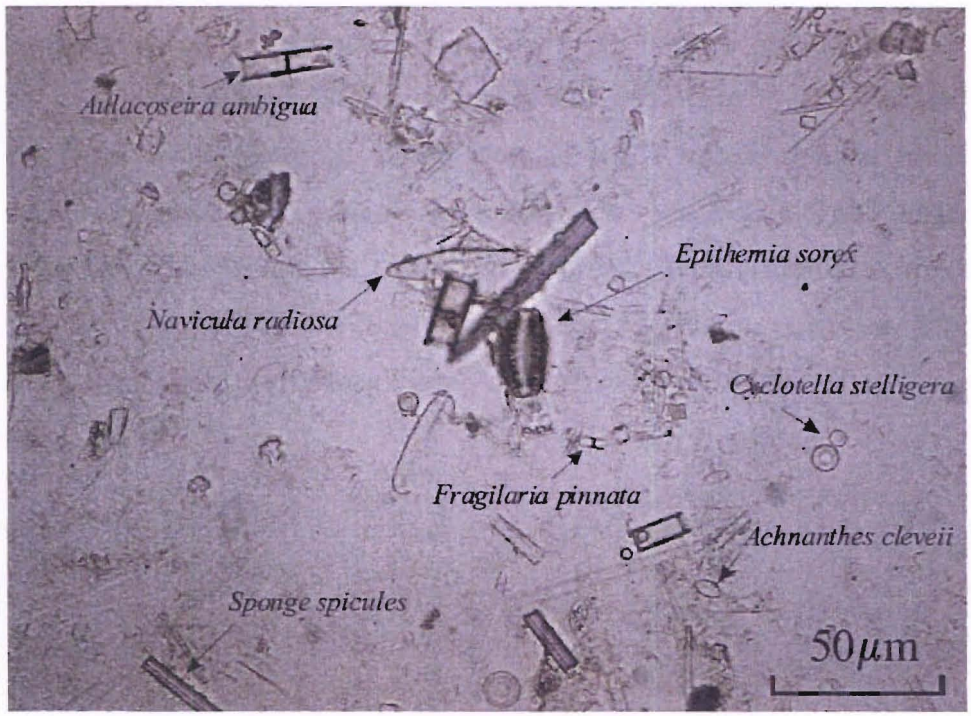


Figure 5.9: Sample view from RgZ2 section

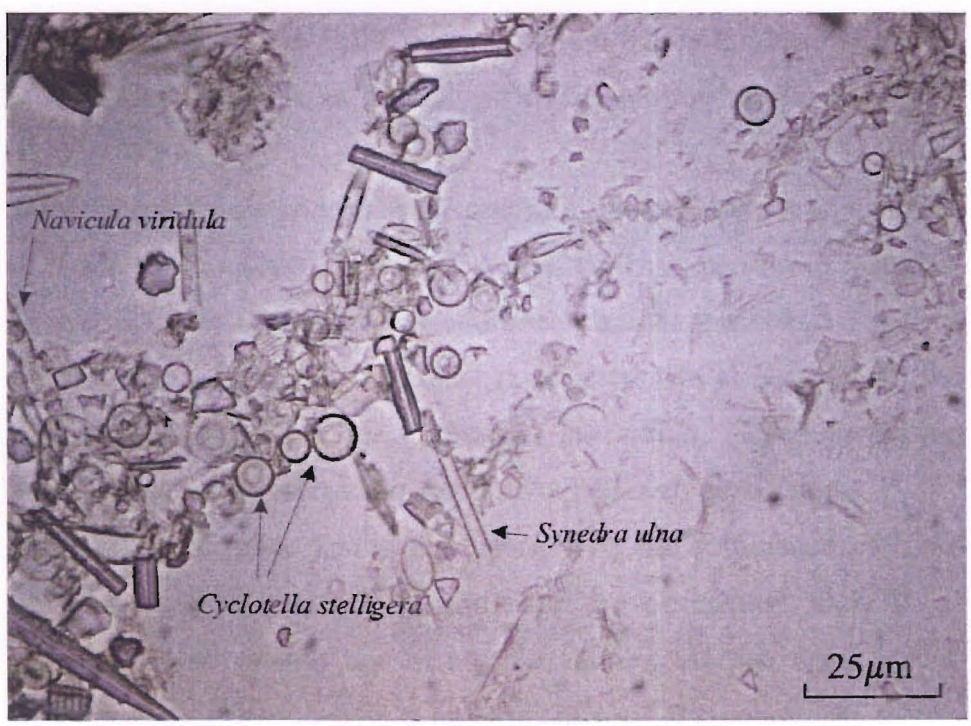


Figure 5.10: Sample view from RgZ3 section

Rangitoto Zone 3 (29.25 cm - 19.75 cm)

RgZ3 extends from 29.25 cm to the top of the section, at 19.75 cm. RgZ3 is characterised by *C. stelligera* being the dominant taxa, with 71%. All other prominent species decline significantly: *A. ambigua* to 5%, *S. ulna* to 2%,

Stephanodiscus spp. to less than 1%, *F. pinnata* to 3% while *F. crotonensis* disappears from the lake altogether at the beginning of the zone (Fig. 5.10). Other taxa to disappear from the assemblage at the start of RgZ3 are *Fragilaria brevistriata*, *Fragilaria capucina* v *vaucheriae*, *Navicula cuspidata* and *Stauroneis phoenicenteron*. In addition, six taxa are only present within this zone: *Achnanthes exigua* v *elliptica*, *Rhopalodia novae zealandiae*, *Mastogloia elliptica*, *Pinnularia* spp., *Eunotia* spp., and *Achnanthes lanceolata* v *frequentissima*.

5.1.2 Pukaki Crater

5.1.2.1 P40(T5)

P40(T5) is a 2 mm thick andesitic tephra recorded at a depth of 6102 cm, in core run 40. T5 is the thinnest tephra sampled and investigated. 16 samples were collected across the tephra bed – from 6109.45 cm (7.25 cm below the base of the tephra) to 6089.75 cm (12.25 cm above the tephra), giving a sampling section covering 19.7 cm (Fig. 5.11).

18 diatom species were present in the section – making it the least diverse of those sampled. *Cyclotella stelligera* is the only taxon which is present in numbers greater than 5%, and *Synedra ulna*, the only additional taxa at more than 1% (Fig. 5.12). However, at any one level, six additional taxon comprise at least 1% of the count: *Fragilaria capucina* v *vaucheriae*, *Cocconeis placentula*, *Gomphonema parvulum*, *Fragilaria pinnata*, *Achnanthes exigua* and *Achnanthes* cf. *minutissima*.

No changes are recorded across the tephra, with the dominance of *C. stelligera* remaining unaltered, so only one diatom zone can be created. Only in the basal sample does a second diatom rise to notable values. At this depth, 6109.45 cm, *Fragilaria capucina* v *vaucheriae* comprised 14% of the count. In the following sample, *F. capucina* v *vaucheriae* drops immediately to <1% and remains at this level until it disappears from the lake after 6102.25 cm. Two species are only present in the pre-tephra sediments; *Amphora libyca* and *Cymbella affinis*, with two species, *Epithemia sorex* and *Navicula placentula*, only appearing in post-tephra deposits.

P40(T5) tephra - andesitic (2 mm thick)

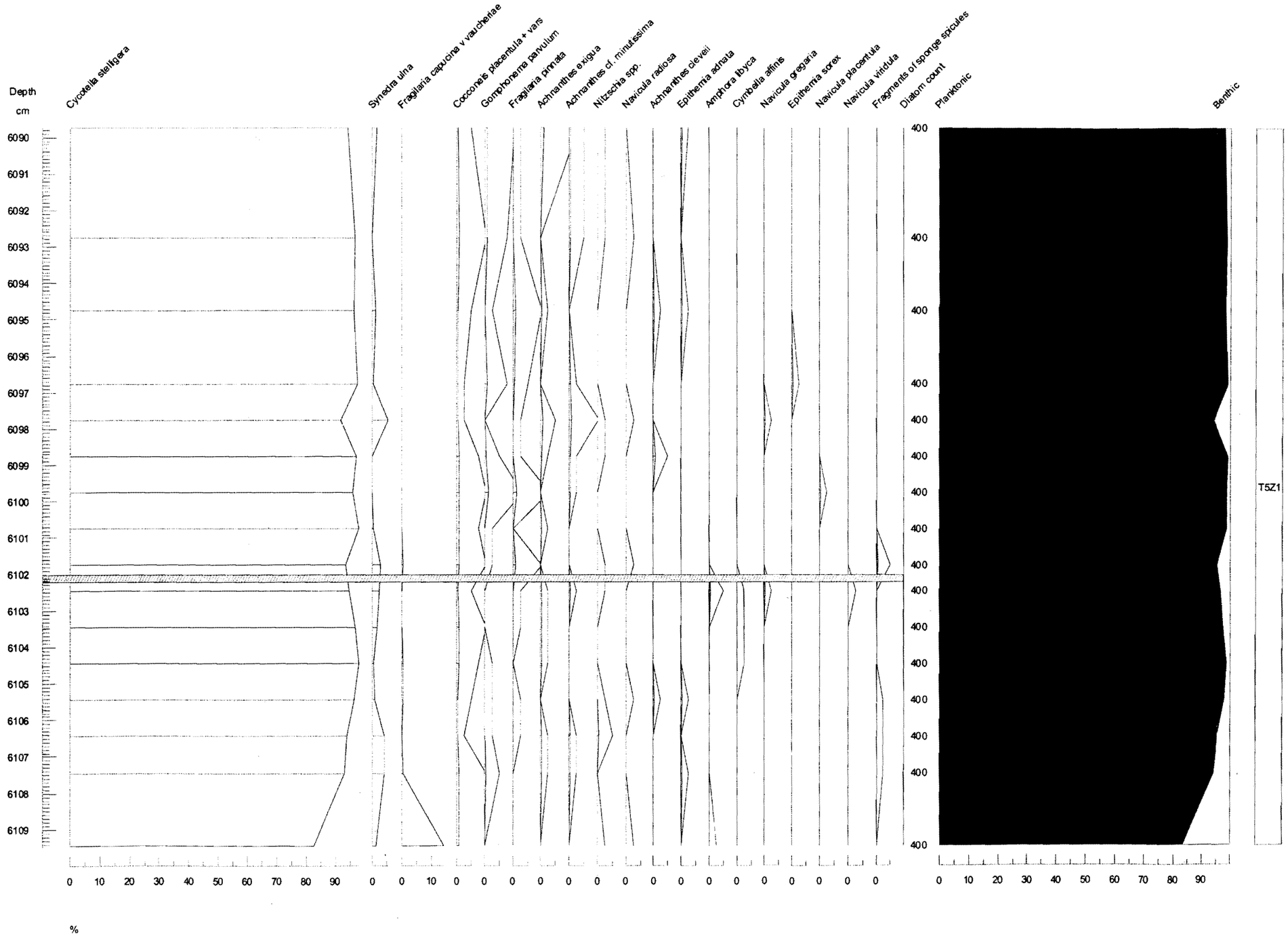


Figure 5.11: Diatom taxa identified across T5 tephra with x10 exaggeration of taxa <0.9% of total count

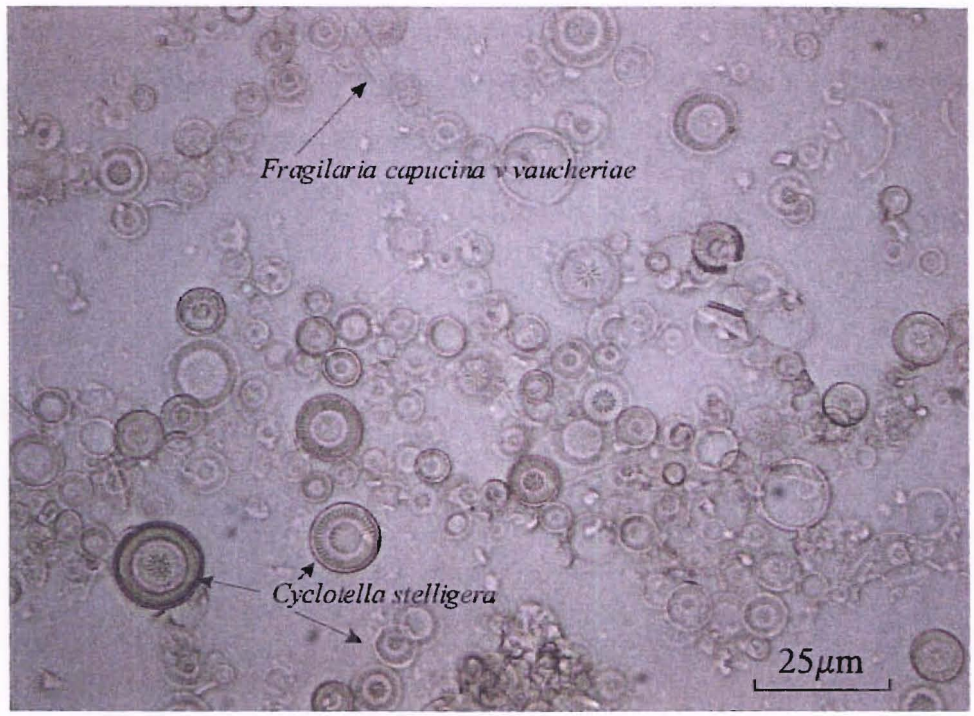


Figure 5.12: Sample view from T5 tephra section

5.1.2.2 P36(T6)

T5 is a 5 mm thick basaltic tephra preserved at 5440 cm. 16 samples were taken either side of the tephra covering 20 cm, from 5447.75 cm (7.25 cm below the tephra) to 5427.75 cm (12.25 cm above the tephra) (Fig. 5.14). 29 diatom species were identified in the section. Only three species occur at values above 5%: *Cyclotella stelligera*, *Synedra ulna* and *Synedra ulna* v *spathulifera*, with *Cocconeis placentula* occurring at more than 1%. 9 additional diatom species make up greater than 1% of counts at individual levels: *Gomphonema parvulum*, *Fragilaria pinnata*, *Achnanthes cleveii*, *Achnanthes exigua*, *Epithemia sorex*, *Nitzschia* spp., *Cymbella affinis*, *Stephanodiscus alpinus* and *Epithemia adnata*.

The individuals identified as *Synedra ulna* v *spathulifera* appear to be an teratological form of *S. ulna* v *spathulifera* or *S. acus* because of the shape and geometry of the axial region of the frustules. As shown in Fig. 5.13a, the shape of the axial region of a standard *S. ulna* v *spathulifera* is straight and linear, whereas in the specimens present in this section they have more irregular, curved axial regions (Fig. 5.13b) (e.g. Patrick & Reimer, 1966). Teratological forms are morphologically altered by possessing asymmetric valves or irregular ornamentation. Formation of these aberrant forms is believed to be the result of heavy metal contamination, which

causes either a mutation, or some physical damage during cell development - "developmental asymmetry" (L. Bahls, pers. comm., 1997). In all figures and text, this group will be referred to as *S. ulna* v *spathulifera*.

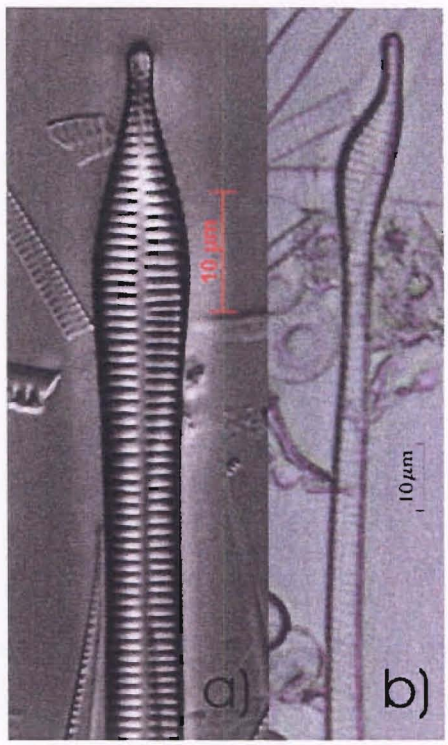


Figure 5.13: *S. ulna* v *spathulifera* (a), and its aberrant form (b) (Source: a. M. Reid, 2003).

There are significant changes in the composition of the diatom assemblage throughout the section, and based on these, 5 diatom zones have been formed (Fig. 5.14).

T6 Zone 1 (5547.75 cm – 5545.25 cm)

T6Z1 begins at the base of the section, extending to 5545.25 cm. *C. stelligera* is the dominant taxon, with 61%. This zone is also characterised by low *S. ulna* (9%) and high *S. ulna* v *spathulifera* (26%).

T6 Zone 2 (5545.25 cm – 5542.25 cm)

T6Z2 records *C. stelligera* and *S. ulna* being co-dominant, with 48% and 47% respectively. *S. ulna* v *spathulifera* drops to 3%.

P36(T6) tephra - basaltic (<5 mm thick)

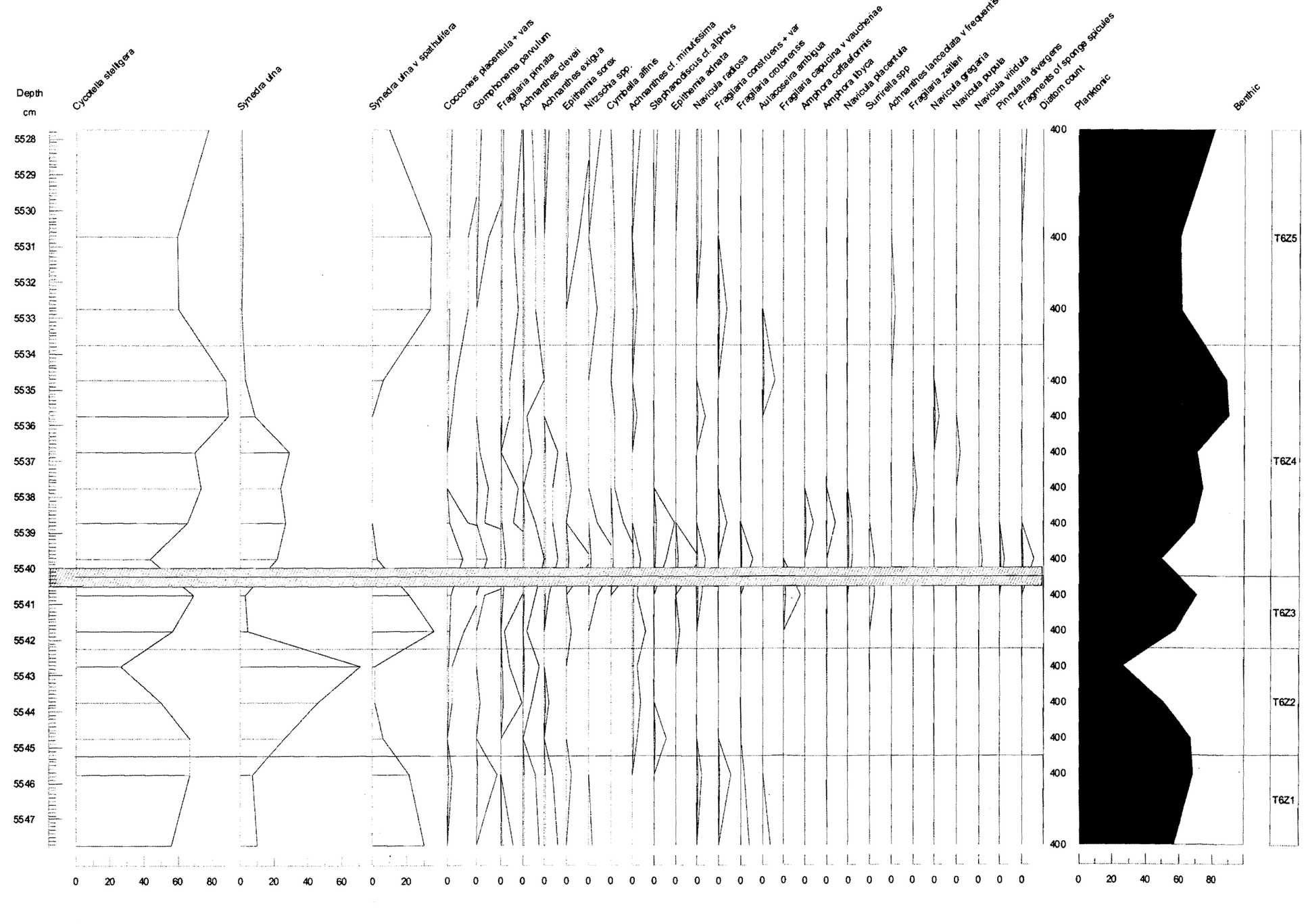


Figure 5.14: Diatom taxa identified across T6 tephra with x10 exaggeration of taxa <1.3% of total count

T6 Zone 3 (5542.25 cm – 5540.25 cm)

In T6Z3, *C. stelligera* and *S. ulna* v *spathulifera* increase to 63% and 29% respectively, while *S. ulna* drops to 3% (Fig. 5.15). One taxon, *Fragilaria capucina* v *vaucheriae*, is present only within this zone.

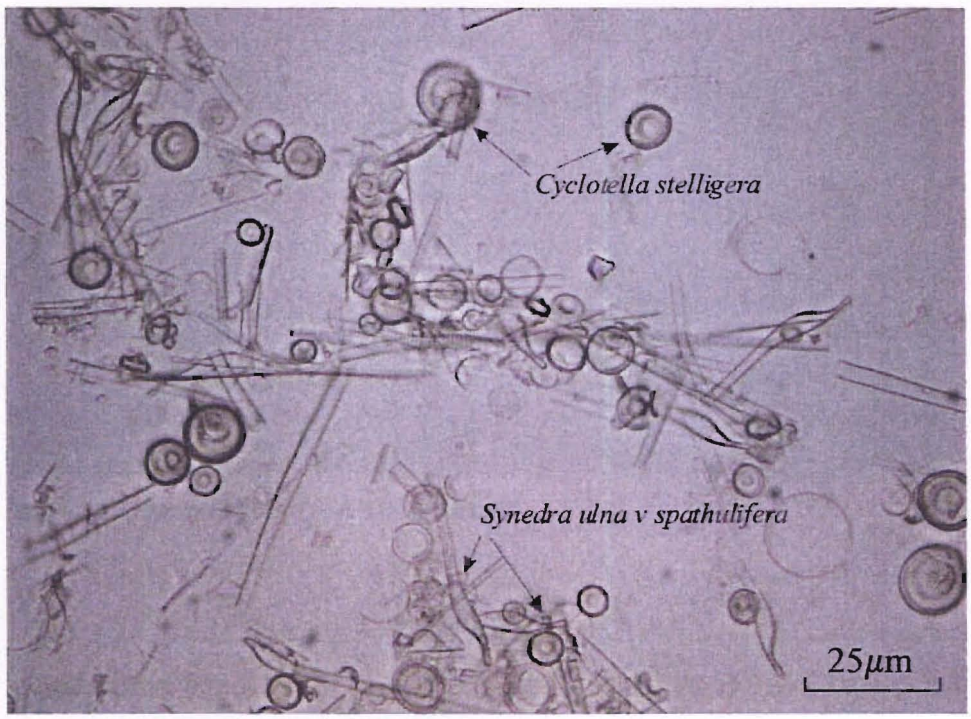


Figure 5.15: Sample view from T6Z3 section

T6 Zone 4 (5540.25 cm – 5533.75 cm)

T6Z4 begins within the tephra bed, and continues to 6.25 cm above the top of the tephra bed, to 5533.75 cm. *C. stelligera* dominates the zone, at 72%, followed by *S. ulna*, *C. placentula*, *S. ulna* v *spathulifera*, *G. parvulum* and *F. pinnata* with 19%, 1.9%, 1.5%, 1.4% and 1% respectively (Fig. 5.16). This zone is characterised by the disappearance of *S. ulna* v *spathulifera* for a 4 cm period beginning at 5538.75 cm, and appearing <2% for the remainder of the zone. In addition, the first sample within the zone contains many taxa that are not present in any other sample. These taxa include *Amphora coffaeformis*, *Amphora libyca*, *Navicula placentula*, *Surrirella spp*, *Fragilaria zeilleri*, *Navicula gregaria*, *Navicula pupula*, *Navicula viridula* and *Pinnularia divergens*.

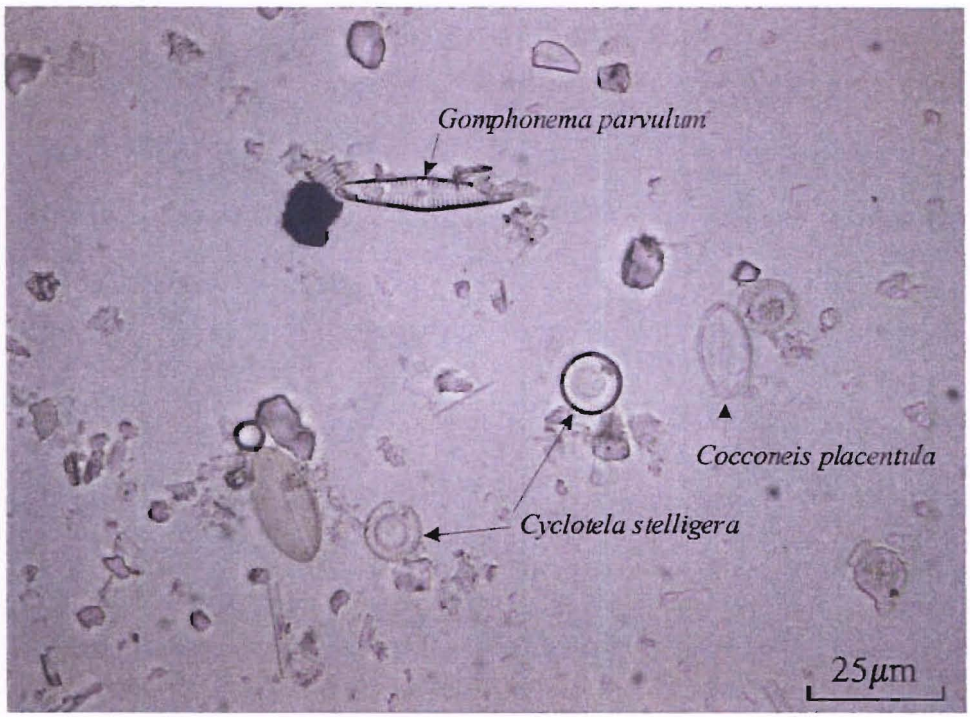


Figure 5.16: Sample view from T6Z4 section

T6 Zone 5 (5533.75 cm – 5527.75 cm)

T6Z5 extends from 5533.75 cm to the top of the section, at 5527.75 cm. *C. stelligera* is the dominant taxa, but drops to 66%, followed by *S. ulna* v *spathulifera* which increases to 26%. *S. ulna* remains low, accounting for <1% of the count within the zone. One taxon, *Achnanthes lanceolata* v *frequentissima*, is recorded only in this zone.

5.1.2.3 P36(T4) (22.5 ka)

Tephra T4 is a 7 mm thick rhyolitic tephra recorded at 5486.5 cm. 16 samples were collected from 5494.45 cm (7.2 cm below the tephra) to 5474.25 cm (12.25 cm above the tephra), producing a section length of 20.2 cm (Fig. 5.17).

20 diatom species were identified in these samples, of which three, *Cyclotella stelligera*, *Synedra ulna* and *Synedra ulna* v *spathulifera*, account for more than 5%, with no further taxa with at least 1% total abundance, although five comprise at least 1% of the count in at least one level: *Fragilaria pinnata*, *Cocconeis placentula*, *Gomphonema parvulum*, *Achnanthes cleveii* and *Fragilaria construens*.

P36(T4) tephra - rhyolitic (7 mm thick)

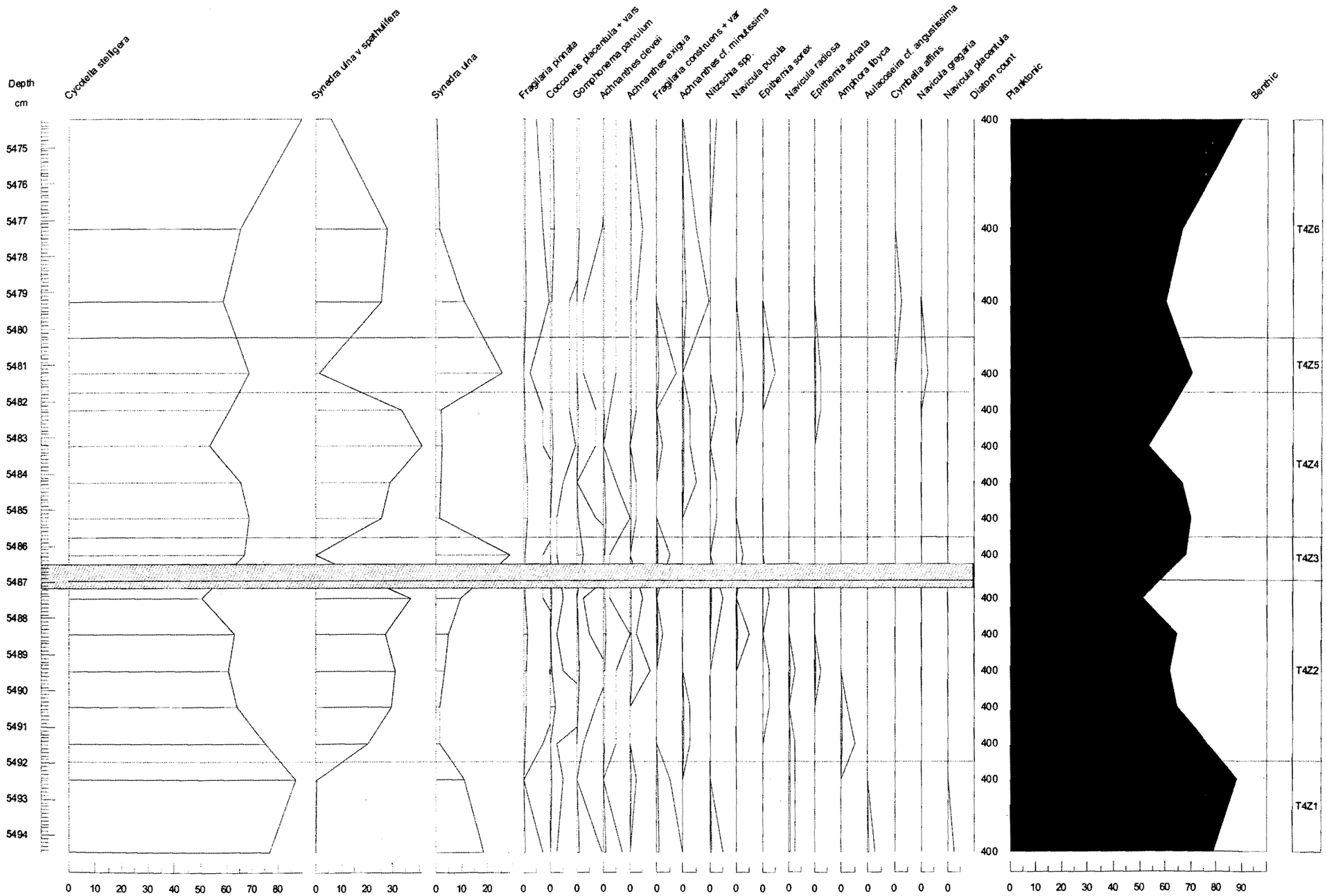


Figure 5.17: Diatom taxa identified across T4 tephra with x10 exaggeration of taxa <0.9% of total count

The composition of the diatom assemblage undergoes significant changes within the section, and based on these recorded changes, six diatom zones can be formed.

T4 Zone 1 (5494.45 cm – 5491.95 cm)

T4Z1 extends from the base of the section (5494.45 cm) to 5491.45 cm, and is characterised by high counts of *C. stelligera* (82%) and *S. ulna* (15%). Conversely, *S. ulna* v *spathulifera* is very rare, at <0.1%. *Navicula placentula* and *Aulacoseira ambigua* are only found in this zone.

T4 Zone 2 (5491.95 cm – 5486.85 cm)

T4Z2 is characterised by *S. ulna* v *spathulifera* increasing to 29% (Fig. 5.18). Additionally, the count of *C. stelligera* drops to 62%, as does *S. ulna* to 4%. *Amphora libyca* is the only taxon which is restricted to within this zone.

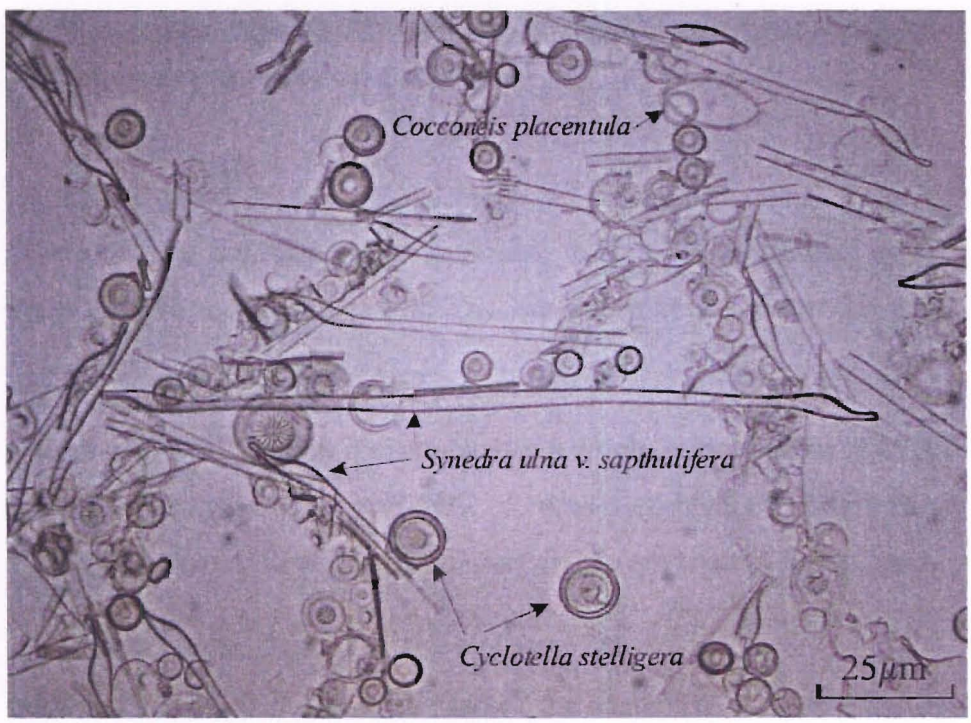


Figure 5.18: Sample view from T4Z2 section

T4 Zone 3 (5486.85 cm – 5485.75 cm)

T4Z3 encompasses only a single sample, immediately above the tephra layer at 5486.25 cm. Within this zone, *S. ulna* v *spathulifera* disappears completely from the assemblage while *S. ulna* accounts for 29% (5.19). *C. stelligera* remains the dominant taxon, with 67%. No taxa are present only within this zone, with *Navicula radiosa*, disappearing from the assemblage at this point, and does not return.

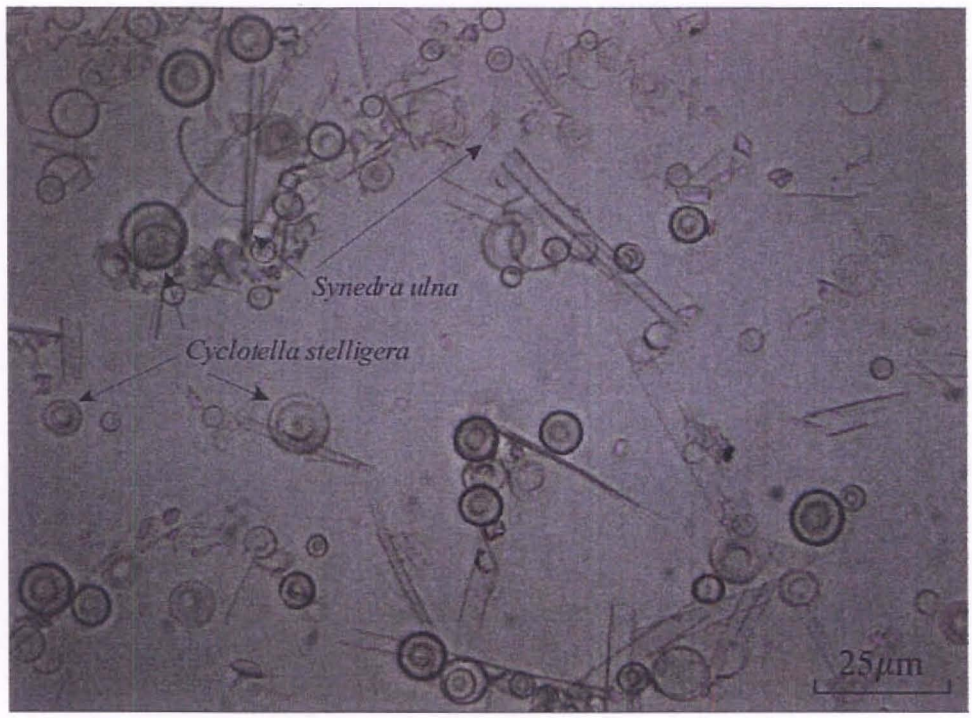


Figure 5.19: Sample view from T4Z3 section

T4 Zone 4 (5485.75 cm – 5481.75 cm)

C. stelligera is the dominant taxa in T4Z4, with 62%, followed by *S. ulna* v *spathulifera* with 32% and *S. ulna* with 2%. No taxa are restricted to this zone.

T4 Zone 5 (5481.75 cm – 5480.25 cm)

T4Z5 is similar to T4Z3 in that it encompasses a single sample, from 5481.25 cm. *C. stelligera* is the dominant taxa, with 69%. *S. ulna* v *spathulifera* drops to just 1.5%, while *S. ulna* increases to 26%. *Navicula gregaria* is only found in this zone.

T4 Zone 6 (5480.25 cm – 5474.25 cm)

T4Z6 extends from 5480.25 cm to the top of the section of core, at 5474.25 cm. In this zone, *C. stelligera* remains the dominant taxa, with 71%, followed by *S. ulna* v *spathulifera* which increases to 20%, whereas *S. ulna* drops to 4%. *Cymbella affinis* is only present in T4Z6.

5.1.2.4 P36(T3)

Tephra T3 is a 5 mm thick andesitic tephra recorded at a depth of 5481.5 cm. Across the tephra 16 samples were collected, producing a section covering 19.5 cm from 5489.25 cm (7.25 cm below the tephra) to 5469.75 cm (11.75 cm above the tephra).

P36(T3) - andesitic (5 mm thick)

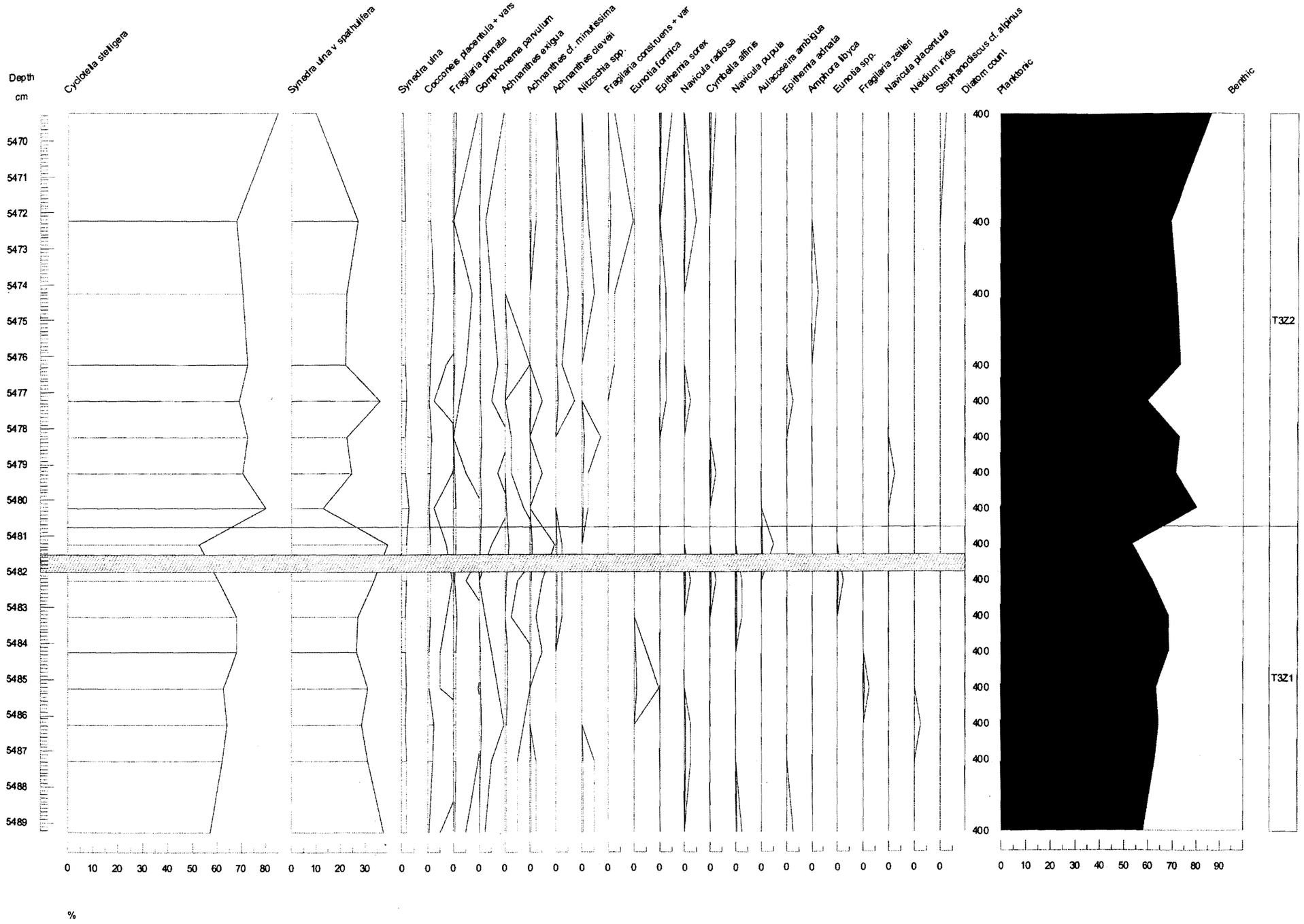


Figure 5.20: Diatom taxa identified across T3 tephra with x10 exaggeration of taxa <1.1% of total count

23 diatom species were identified in the section (Fig. 5.20). *Cyclotella stelligera* and *Synedra ulna* v *spathulifera* are the only two taxa that account for more than 5% of the total count, with *Synedra ulna* and *Cocconeis placentula* the only additional taxon with more than 1% (Fig. 5.21). Concerning individual samples, 6 additional taxa; *Fragilaria pinnata*, *Gomphonema parvulum*, *Achnanthes exigua*, *Achnanthes minutissima*, *Fragilaria construens* and *Eunotia formica* are present in populations of at least 1% of the count.

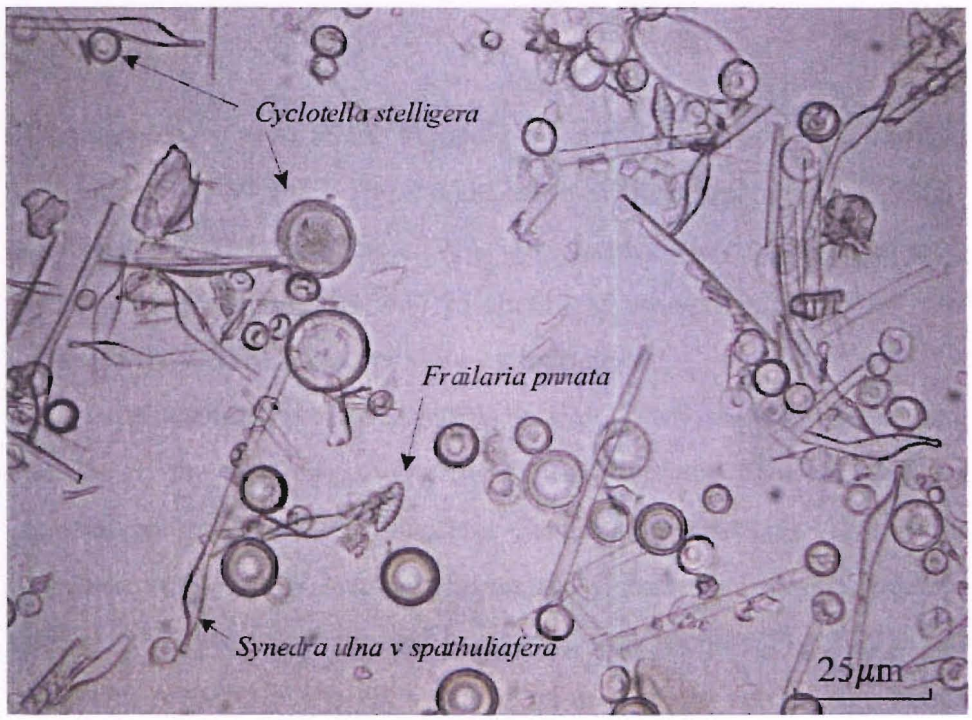


Figure 5.21: Sample view from T3 tephra section

Based on the diatom assemblage within the section, two diatom zones can be created (Fig. 5.20).

T3 Zone 1 (5489.25 cm – 5480.75 cm)

T3Z1 covers 9 cm from the base of the section (5489.25 cm) to 5480.75 cm, which is slightly above the top of the tephra bed. Within this zone, *C. stelligera* is the dominant taxa, with 62%, followed by *S. ulna* v *spathulifera*, at 32%. The end of this zone is marked by a trend of increasing *S. ulna* v *spathulifera* and decreasing C. *stelligera*. *Eunotia formica*, *Navicula pupula*, *Aulacoseira ambigua*, *Fragilaria zeilleri* and *Neidium iridis* are only present within this zone.

T3 Zone 2 (5480.25 cm – 5469.25 cm)

T3Z2 extends from 5480.25 cm to the top of the section (5469.25 cm) – a distance of 12 cm. T3Z2 is characterised by a sudden increase in *C. stelligera*, to 72%, while S. ulna v spathulifera drops to 22%. Five diatom species are present only in this zone: *Fragilaria construens*, *Epithemia sorex*, *Amphora libyca*, *Navicula placentula* and *Stephanodiscus* cf. *alpinus*.

5.1.2.5 P36 (T2)

Tephra T2 from core run 36 of the Pukaki 1-01 core is a 20 cm thick basaltic tephra recorded at a depth of 54.5 m. This makes it the thickest tephra sampled from either Lake Pupuke or Pukaki Crater (Fig. 5.22). 16 samples were collected from 5577.25 cm (7.25 cm below the tephra) to 5537.75 cm (12.25 cm above the tephra), covering a length of 39.5 cm. 400 frustules per slide were counted.

23 diatom species were identified in this section. Two of these taxa accounted for more than 5% of the total count: *Cyclotella stelligera* and *Synedra ulna*, with one further species comprising more than 1%: *Cocconeis placentula*. Three additional taxa, *Fragilaria pinnata*, *Achnanthes exigua* and *Achnanthes minutissima*, compose more than 1% in at least one individual level within the section (Fig. 5.23).

While no major shifts in the composition of the diatom assemblage occur across the tephra, based on the relative proportions of the two dominant species across the tephra, three diatom zones can be created (Fig 5.22).

T2 Zone 1 (5477.25 cm – 5470.75 cm)

T2Z1 extends from the base of the section, 5477.25 cm, to 5470.75 m. *C. stelligera* dominates the zone with 60%, followed by *S. ulna*, at 35% and *F. pinnata* with 1%. In addition, two species, *Fragilaria crotonensis* and *Rhopalodia novae zealandiae* are found exclusively in this zone.

T2 Zone 2 (5470.25 cm – 5443.75 cm)

T2Z2 begins immediately below the tephra, at 5470.75 cm and extends to 5443.75 cm. This zone is characterised by an increase of *C. stelligera* to 82%, while *S. ulna* decreases to 15%. Two species that occur in T2Z1 and T2Z3, *Cymbella affinis* and *Aulacoseira ambigua*, do not occur in T2Z2, while three other taxa, *Eunotia* spp., *Navicula placentula* and *Navicula pupula* are only present in T2Z2.

P36 (T2) tephra - basaltic (200 mm thick)

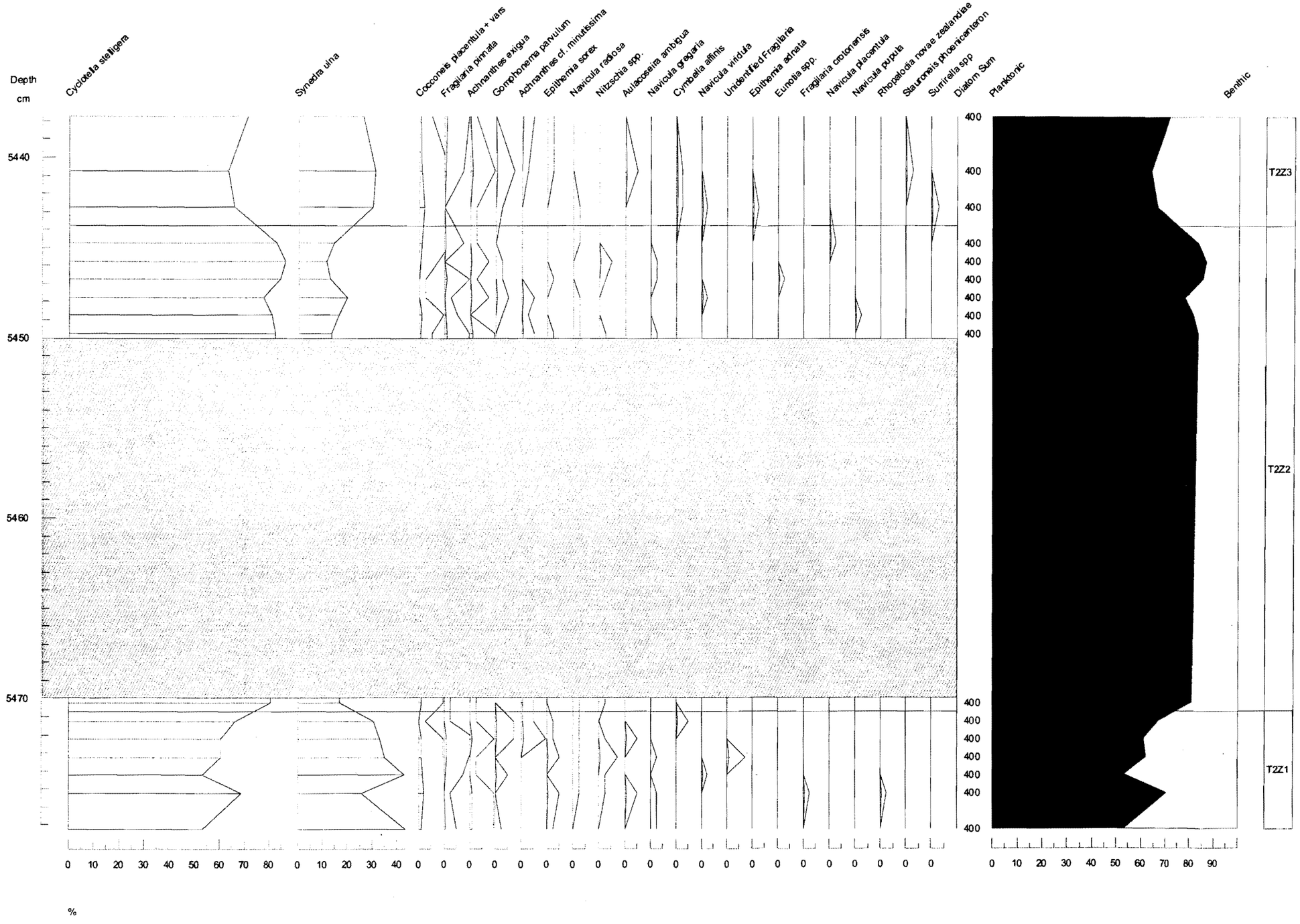


Figure 5.22: Diatom taxa identified across T2 tephra with x10 exaggeration of taxa <1.1% total count

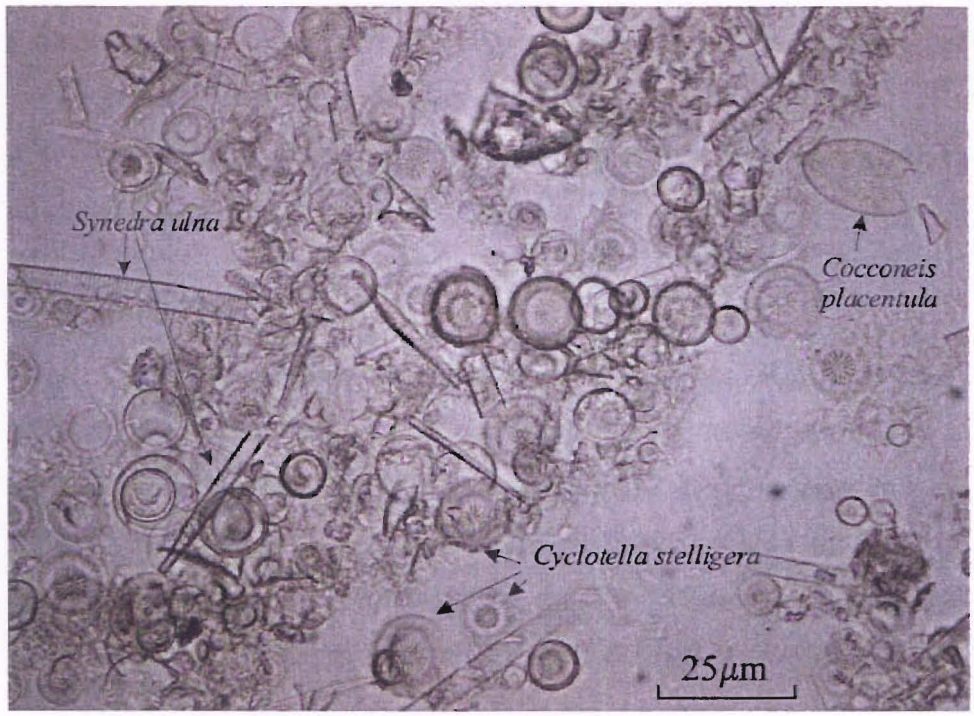


Figure 5.23: Sample view from T2 tephra section

T2 Zone 3 (5443.75 cm -5437.75 cm)

T2Z3 begins at 5444.75 cm and continues to the top of the section, 5437.75 cm. *C. stelligera* decreases in T2Z3, to 67%, and *S. ulna* increases to 29%. *Nitzschia* spp. and *Navicula gregaria*, two rare taxa present previously, disappear in T2Z3, while three taxa, *Epithemia adnata*, *Stauroneis phoenicenteron* and *Surrirella* spp. are only present in this zone.

5.1.3 Overview:

5.1.3.1 Lake Pupuke

Cyclotella stelligera is the dominant species in the Lake Pupuke core, with 36% of the diatom population across all the samples collected from the core. *Fragilaria pinnata* and *Aulacoseira ambigua* each comprise 18% with *Synedra ulna* making up 9% of the total. The only other species to make up more than 1% of the total abundance is *Cocconeis placentula* with 1.1%. Sponge spicules are also prominent, with 3% of the total count. The total abundance explained by the species (including sponge spicules) which make up greater than 1% of the population is 86%.

The Rangitoto tephra is the only tephra across which a complete diatom assemblage change is recorded. However, the other sections all record changes of varying magnitude, duration and character across the respective tephras. These will be discussed in the Chapter 7.

5.1.3.2 Pukaki Crater

In Pukaki Crater, *C. stelligera* is dominant, comprising 73% of the population. The only other species that make up more than 1% are *S. ulna* v *spathulifera* and *S. ulna* with 12% and 11% respectively, although the latter is only present in three of the five sections. Even though fewer species are prominent within the core, the total abundance explained by these species is high, at 96%. This is because of the almost complete dominance of *C. stelligera* in all the sections analysed. Two events (T2 & T3) show changes in the relative proportion of the dominant species across, but not coincidental with, the tephra bed. Multiple changes are recorded across T4 & T6, with regard to *S. ulna* and *S. ulna* v *spathulifera*, some concurrent with the tephra, others not, and T6 shows a significant increase in diversity immediately above the tephra beds. T5 shows no change across the tephra, with the dominance of *C. stelligera* continuing unchanged. The nature, size and duration of these changes will be discussed in Chapter 7.

5.2 *Diatom density data*

The addition of lycopodium spores at the preparation stage, as outlined in chapter 4, was intended to enable the calculation of diatom concentrations at all levels sampled within the cores, with the intent of illustrating any changes in the concentration of diatoms within each section, specifically across the tephras. However, as will be outlined below, this method was ultimately of little use.

5.2.1 Lake Pupuke

Lycopodium spores were recorded in only 6 of the 64 samples analysed from the Lake Pupuke core, four from across the Rotoma tephra and two in the Rangitoto section. Additionally, only single lycopodium spores were present in each of these samples.

This means that a quantitative calculation of diatom concentration cannot be performed, as much larger numbers of spores are required to produce a meaningful result. Instead, all that can be done is to calculate a general diatom concentration for the samples where lycopodium spores were encountered and a minimum diatom concentration for the samples where spores were not found based on using one spore present as the minimum concentration.

The results produced by this method are: for the Rangitoto tephra section, diatom concentrations of between at least 3.5 x 10^5 diatoms per cm^3 and at least 7.1 x 10^5 diatoms per cm^3 for the section. For the Tahua tephra, concentrations of at least 5.3 x 10^5 diatoms per cm^3 and at least 7.1 x 10^5 diatoms per cm^3. For the Taupo tephra, concentrations of at least 7.1 x 10^5 diatoms per cm^3, and for the Rangitoto tephra concentrations of 7.1 x 10^5 diatoms per cm^3 and at least 7.1 x 10^5 diatoms per cm^3.

5.2.2 Pukaki Crater

No lycopodium spores were recorded in any section analysed from the Pukaki Crater core. Therefore, a minimum concentration of 7.1 x 10^5 diatoms per cm^3 for all of the sections analysed is all that can be achieved.

5.2.3 Summary

A prominent part of any analysis of environmental changes on diatoms involves determining changes in diatom concentration. This is especially relevant across tephra events because a large number of previous studies have reported changes in concentration across tephra events (e.g. Kurenkov, 1966; Barsdate & Dugdale, 1972; Harper *et al*, 1986; Hickman & Reasoner, 1994; 1998; Barker *et al*, 2000). While comparative analysis of diatom concentrations is not possible, the available figures indicate a very high concentration of diatoms living within the lake.

Chapter six: Autecological and Sediment Geochemistry data

6.1 *Environmental Indicator Data*

This data is compiled using a slightly modified version of the checklist produced by Van Dam *et al* (1994), which lists the environmental optima for over 700 individual diatom taxa. This checklist details the preferences for pH, salinity, nitrogen availability, oxygen saturation and trophic status levels within the occupying water body. By using this autecological data set, the conditions within the lake at over the periods analysed can be determined.

6.1.1 Lake Pupuke

6.1.1.1 Rotoma tephra

pH

Analysis of the diatom assemblage across the Rotoma tephra utilizing the checklist produced by Van Dam *et al* (1994) demonstrates that the lake was dominated by alkaliphilous taxa (Fig. 6.1). These taxa comprise between 85% and 96% of the species at all levels. Alkalibiontic taxa followed, with an average of 4%. The results illustrate that the pH of the lake at the time of input of the Rotoma tephra would have been slightly above 7.0

Across the tephra, the pH does not change markedly, with alkaliphilous taxa remaining the key group. Circumneutral taxa do show a slight increase immediately above the tephra, while alkalibiontic decline slightly. These changes are marginal and unlikely to be of significance.

Salinity

Fresh-brackish taxa dominate Lake Pupuke across the entire section; accounting for 97% of all species at all levels (Fig. 6.1). This represents a salinity of <0.09%, which

corresponds to a fresh-water lake. There are no changes recorded across the tephra bed.

Nitrogen Uptake

Nitrogen-autotrophic taxa dominate the section, accounting for between 93% and 99% of species at all levels (Fig. 6.1). Nitrogen-autotrophic taxa have low N requirements relative to other taxa. These results indicate that the level of organically bound nitrogen available was low throughout the section.

Oxygen Requirements

Taxa that require high levels of oxygen are the most numerous groups across the Rotoma tephra (Fig. 6.1). In pre-tephra sediments, taxa that require very high levels of saturated oxygen (about 100%) make up 52% of the assemblage, with taxa that require lower concentrations being less abundant. Across the tephra bed, taxa that require lower levels become more abundant, predominantly 'high' oxygen demanding taxa. There is a large degree of fluctuation in oxygen saturation levels within the zone. Because of this, any significant patterns are difficult to extract.

Trophic Status

Indifferent taxa dominate the nutrient status record across the Rotoma tephra, at 57% (Fig. 6.1). The influx of the tephra does not significantly alter the long-term nutrient level within the lake. However, there is a short-term (4 cm duration) shift towards oligotrophic taxa immediately following the tephra input. Within this zone, oligotrophic taxa increase from a pre-tephra abundance of 26% to 40%, whereas indifferent taxa decline from 61% to 48%. During this period, the other trophic status categories record little change.

Summary

Trophic status appears to be the only autecological parameter that changes across the tephra, recording a short-term increase in oligotrophic taxa.

Rotoma tephra - rhyolitic (50 mm thick)

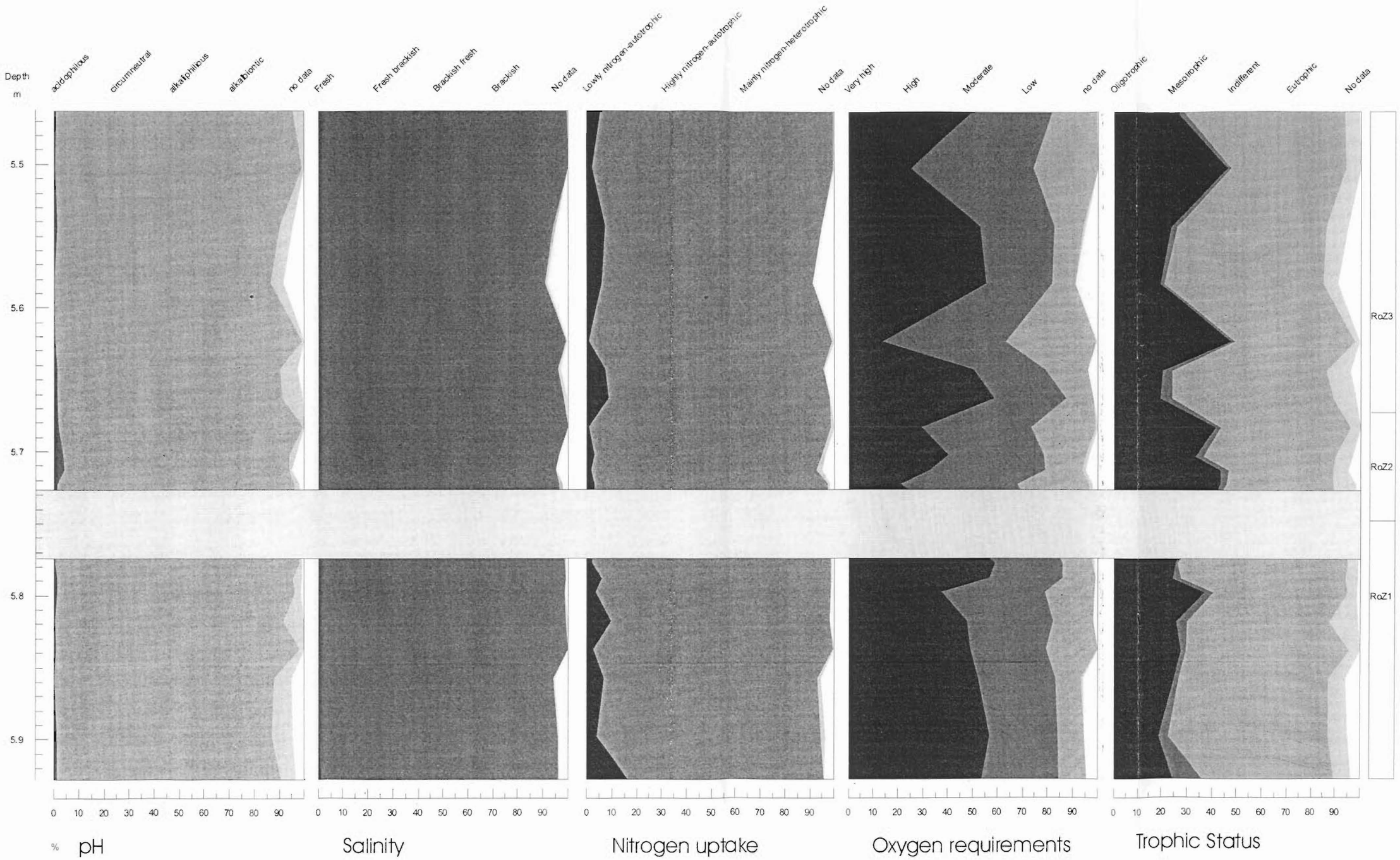


Figure 6.1: Environmental indicators across Rotoma tephra

6.1.1.2 Tahua tephra

pH

Alkaliphilous taxa dominate the section across the Tahua tephra, making up 97% of all taxa counted followed by circumneutral taxa with 2% and alkalibiontic with 1% (Fig. 6.2). Species that prefer acidic waters are not present in this section, therefore, the data indicates a pH of above 7.0. There is no change recorded across the tephra, with alkaliphilous taxa remaining dominant.

Salinity

Fresh-brackish species dominate the section, accounting for 99% of the assemblage (Fig. 6.2). Taxa preferring 'fresh' water are absent, as are brackish taxa. This indicates a salinity of between 0.02% and 0.09%. The input of the Tahua tephra has no effect on salinity, with fresh-brackish taxa remaining the dominant group, indicating a fresh-water lake during the entire section.

Nitrogen Uptake

Nitrogen-autotrophic taxa are the most prominent taxa within the section, accounting for 98% of all species present, with highly nitrogen-autotrophic species the more dominant (Fig. 6.2). Across the Tahua tephra, no major changes are recorded, which indicates that low concentrations of nitrogen compounds are available within the lake for the entirety of the section.

Oxygen Requirements

Taxa requiring 'fairly high' (>75%) levels of oxygen saturation dominate the diatom assemblage across the Tahua tephra (Fig. 6.2). These taxa make up an average of 58%, with 'high,' 'moderate' and low taxa accounting for 19%, 22% and 0.5% respectively. There is a trend of increasing level of 'high' taxa from the base of the core upwards, which comes at the expense of 'very high' and especially 'moderate' taxa. There is no change recorded across the tephra bed, however 1.75 cm above the tephra, 'moderate' taxa decreases rapidly from 26% to 8%, where it continues for the remainder of the section.

Tahua tephra - rhyolitic (10 mm thick)

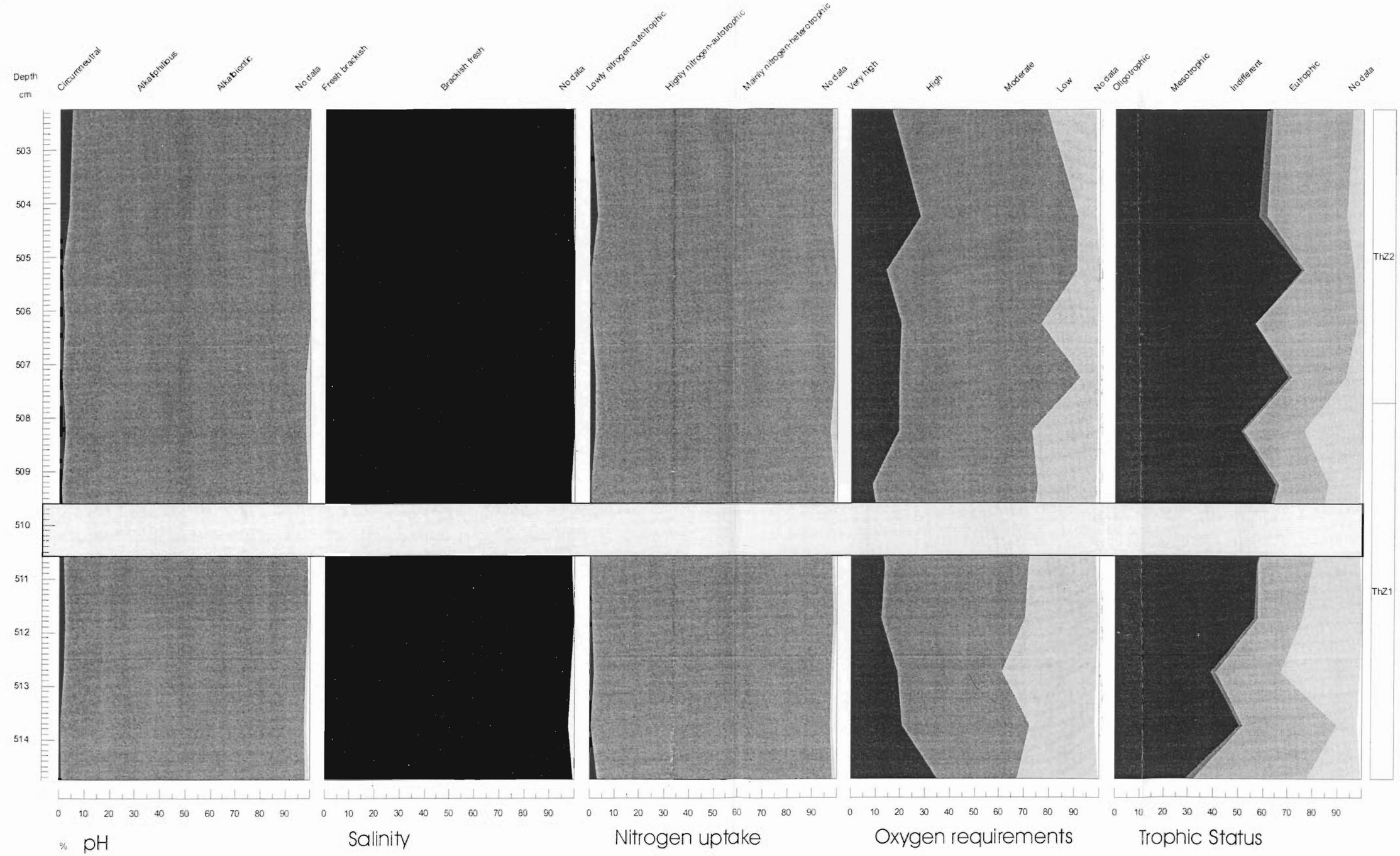


Figure 6.2: Environmental indicators across Tahua tephra

Trophic Status

Species preferring oligotrophic conditions dominate the section, accounting for 56% of the assemblage (Fig. 6.2). These are followed by indifferent taxa, eutrophic taxa and mesotrophic taxa with 28%, 14% and 1.5% respectively. No significant change in trophic status indicators occur simultaneously with the tephra. There is, however, a considerable shift 1.75 cm above the tephra (at 507.25 cm), where the abundance of eutrophic taxa declines significantly. In sediments preceding this sample, eutrophic taxa form 20% of the assemblage, whereas after this depth, this decreases to 5%. Oligotrophic taxa increase their abundance from 49% to 64%. This represents a shift to more oligotrophic conditions at this stage.

Summary

Again, trophic state is the only parameter that records any significant changes within the section, that of a gradual increase in oligotrophic taxa and a loss of eutrophic taxa 1.75 cm above the tephra.

6.1.1.3 Taupo tephra

pH

Alkaliphilous taxa dominate across the Taupo tephra, comprising 96% of the total diatom population in the section (Fig. 6.3). Circumneutral taxa are next with 1.6%, followed by acidophilous taxa with 1.2%. Across the tephra, no major long-term changes are recorded in pH indicators. There is, however, a very small magnitude change recorded immediately above the tephra, with alkalibiontic species increasing by an order of magnitude to ~1.7% from immediately below the tephra, and lasting for 2 cm. The dominance of alkaliphilous taxa along with the presence of alkalibiontic species indicates that the pH was above 7.0.

Salinity

Taxa with optimum salinity ratings of fresh-brackish compose 98% of all diatom taxa recorded across this section (Fig. 6.3). The only other salinity group represented is those which prefer fresh waters, with 1.2%. The dominance of the fresh-brackish group remains unchanged across the tephra.

Nitrogen Uptake

Highly nitrogen-autotrophic taxa dominate the section, accounting for 90% of the assemblage, followed by low nitrogen-autotrophs with 7% and nitrogen-heterotrophs with 1.9% (Fig. 6.3). There are no significant changes recorded across the tephra.

Oxygen Requirements

For the entire section, species that prefer to live in environments with moderate (>50%) levels of oxygen saturation dominate, accounting for 40% of the assemblage (Fig. 6.3). However, 'high' species (>75%) with 37%, and 'very high' (~100%) with 21% indicate that the 'moderate' group does not completely dictate the assemblage. Below the tephra, however, 'high' taxa dominate, followed by 'moderate.' While the composition of oxygen saturation groups changes across the tephra, it does not occur simultaneously with input of the tephra; instead, the change occurs steadily from the base of the section.

Trophic Status

Oligotrophic taxa and eutrophic taxa co-dominate the trophic status record, accounting for 35% and 33% respectively, followed by indifferent taxa with 25% and mesotrophic with 6% (Fig. 6.3). Trophic status undergoes significant changes across the section. In pre-tephra sediments, oligotrophic taxa dominate, followed by eutrophic and indifferent. Then immediately following the top of the tephra bed and continuing for 4 cm, indifferent taxa increase significantly, becoming co-dominant with oligotrophic taxa. Above this level, eutrophic taxa become dominant, followed by oligotrophic and indifferent taxa. This indicates that below the tephra, the lake was generally nutrient poor, then immediately above the tephra, conditions became more variable, and then above this level, high nutrient conditions began to dominate. However, in saying this, it is unusual to have such prominence of both eutrophic and oligotrophic taxa. This implies a stratified lake with low nutrient levels in the plankton habitats, and higher levels on the lake bottom.

Summary

All of the autecological parameters remain constant across the tephra, except trophic state records, which records a short-term increase in indifferent taxa immediately following the tephra.

Taupo tephra – rhyolitic (65 mm thick)

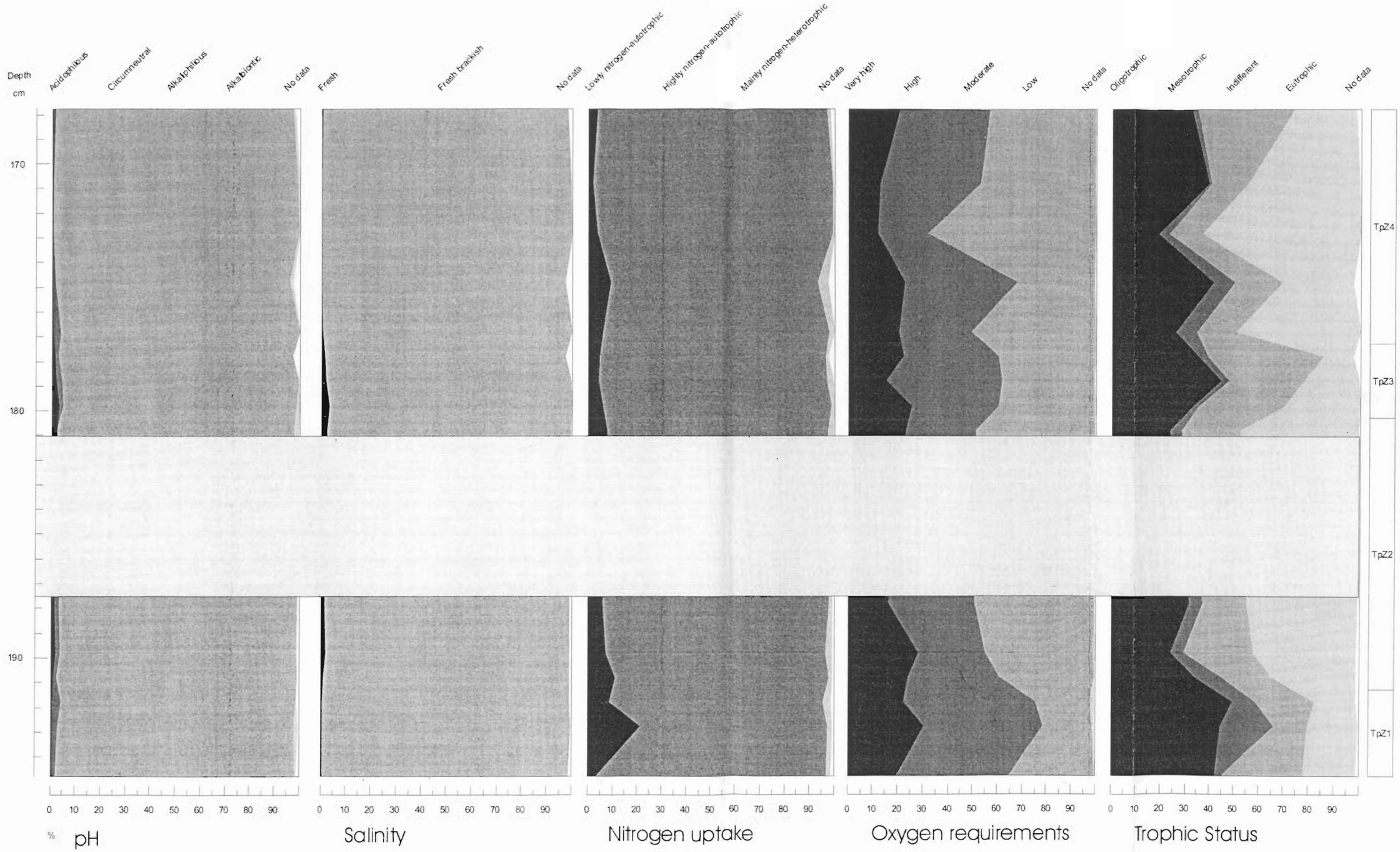


Figure 6.3: Environmental indicators across Taupo tephra

6.1.1.4 Rangitoto tephra

pH

The pH indicator taxa across the Rangitoto tephra signify that Lake Pupuke at the time of influx of the tephra was slightly alkaline. Throughout the section, 87% of the diatom population was composed of alkaliphilous taxa (Fig. 6.4). Acidophilous, circumneutral and alkalibiontic species were also present, accounting for 1%, 3% and 7% respectively. Across the tephra layer, the dominance of alkaliphilous taxa is unaltered, but the abundance of acidophilous taxa decreases, falling from 12% to 2%, while circumneutral taxa increase from 1% to 6%. This data indicates that the pH of the lake decreases across the tephra – falling closer to 7.0.

Salinity

Fresh-brackish taxa dominate the assemblage, accounting for 95% of all species counted (Fig. 6.4). Fresh water taxa are second with 1%, followed by brackish-fresh and brackish with 0.5% and 0.2% respectively. Across the tephra, the dominance of fresh-brackish taxa remains unchanged; however, their abundance decreases from 98% to 93%. This drop is countered by an increase in the group of species which have no recorded preferences.

Nitrogen uptake

Nitrogen-autotrophic taxa are the most abundant within the section, accounting for 87% of the population (Fig. 6.4). Nitrogen-heterotrophs are prominent within pre-tephra sediments, comprising 12%, but their abundance decreases significantly across the tephra, dropping to 1.6% 2 cm above the tephra. The loss of nitrogen-heterotrophs is made up by an increase in autotrophic taxa across the tephra.

Oxygen Requirements

Species which prefer moderate levels of oxygen saturation (>50%) dominate the section, accounting for 74%, followed by 'very high', 'very low' and 'low' with 10%, 6% and 5% respectively (Fig. 6.4). While 'moderate' species remain dominant throughout the section, the relative abundances of the different groups undergo significant changes at two levels within the section. Firstly, beginning 4 cm below the tephra, at 37.75 cm, and ending 2 cm above the tephra, at 28.75 cm, 'moderate' taxa decline from 75% to 64%, while 'high' increases from 3% to 10% and 'very high'

from 10% to 12%. Secondly, from 28.75 cm and continuing to the end of the section, 'moderate' taxa recover to 81%, whereas both 'very high' and 'high' decline; to 9% and 4% respectively. Additionally, taxa preferring very low levels of oxygen saturation drop from an average of 10% to 0.9% at this level.

Trophic Status

Major changes in the trophic status are recorded across the Rangitoto tephra (Fig. 6.4). These changes occur at two levels within the core, at 37.75 cm and 28.75 cm. In the early parts of the section, eutrophic species dominate, accounting for 79% of the population, followed by indifferent species with 11%, and oligotrophic with 6%. The change at 37.75 cm (3.75 cm below the base of the tephra) is characterised by a decrease in eutrophic taxa to an average of 43%, and a corresponding increase in oligotrophic species to 20%, indifferent taxa to 26% and mesotrophic taxa to 9%. The decline of eutrophic species occurs gradually, dropping from 88% to 22% across 7 cm. This gradual change is also recorded in indifferent taxa, whereas oligotrophic species initially increase rapidly, then plateau out. The second shift in trophic status occurs at 28.75 cm. This change is characterised by a sudden and significant rise in oligotrophic species: from 22% to 82% in adjacent samples, and averaging 72% to the top of the section. This increase is countered by declines in all other trophic groups, especially that of eutrophic species, which drops to 9%.

Summary

Major changes are recorded near this tephra, with all parameters recording some form of change. The variable most affected is trophic status, which records a significant shift from eutrophic-dominated to oligotrophic-dominated conditions across, but not concurrent with, the tephra. Other significant changes are recorded in nitrogen and pH.

Rangitoto tephra - basaltic (25mm thick)

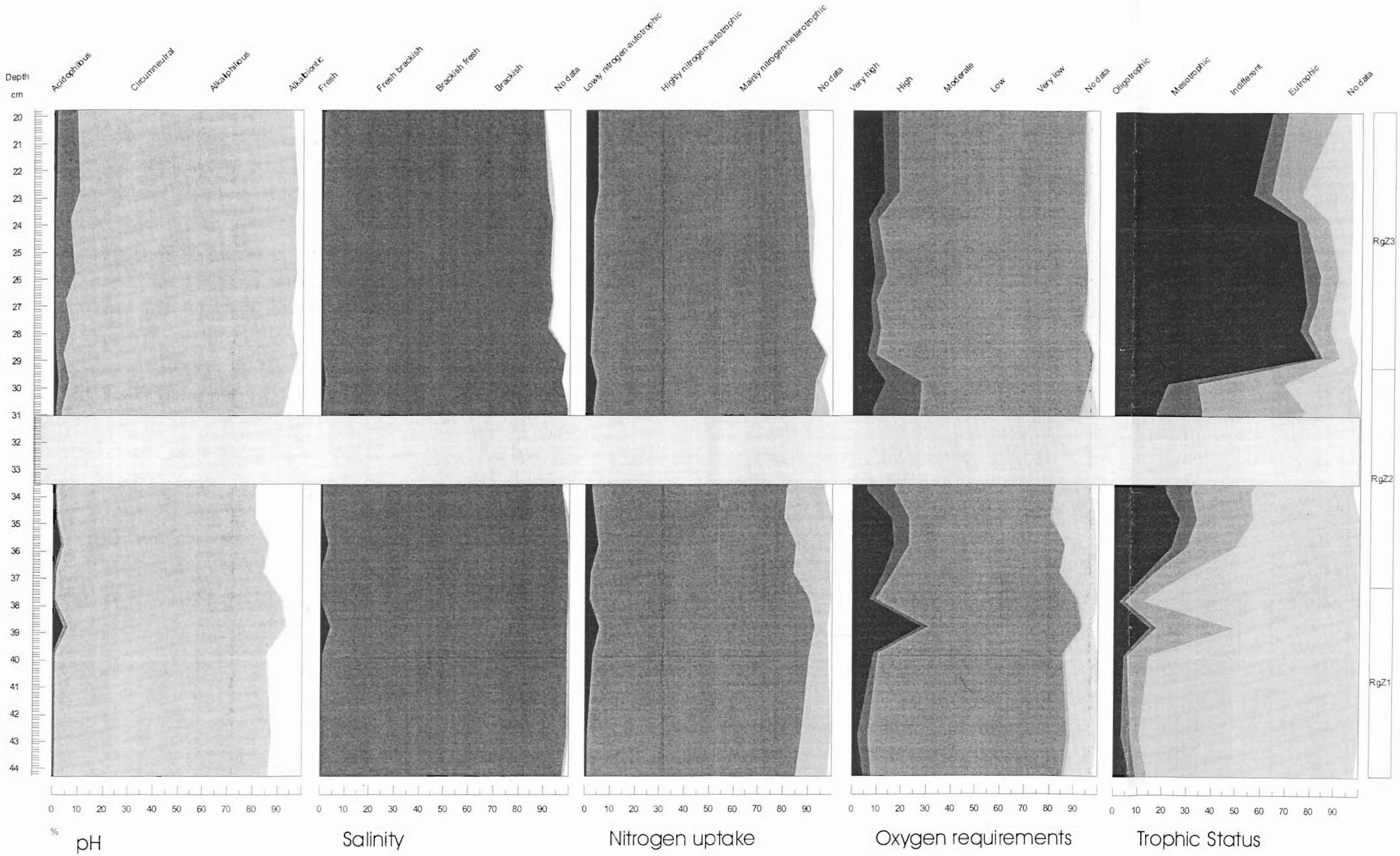


Figure 6.4: Environmental indicators across Rangitoto tephra

6.1.1.5 Lake Pupuke summary

Lake Pupuke records a large amount of variation from the base of the core to the top. Initially, the lake is dominated by benthic taxa, with lake conditions being such that multiple species thrive. However, this changes as you travel up the core, until in the youngest section, planktonic taxa dictate, and aside from the major perturbation recorded within the section, single diatom taxa dominate the assemblage. This could indicate that approximately 9500 years ago, Lake Pupuke was a shallower, more cosmopolitan lake than at 620 years ago. The two remaining sections, 7.0 ka and 1.8 ka, appear to record a broad transitional phase where environmental conditions remained in a semi-stable state for a long period.

While environmental changes are recorded within the core, some environmental parameters remain stable throughout. Lake Pupuke remained a fresh water lake, with a pH of slightly above 7.0, with low levels of organically bound nitrogen available within the water column for the duration of the core. The oxygen saturation record appears to indicate a gradual decrease in saturation levels up the core. The base is dominated by taxa requiring at least 75% and 100% saturation, whereas in subsequent sections, these higher groups are slowly replaced by taxa requiring at least 50% saturation, until at the top of he core, this groups dominates. The trophic status of the lake does not record any such broad trends within the core, instead indicates large-scale fluctuations both within each section, and within the lake as a whole. This signifies that the nutrient levels within the lake was not subject to a long-term controlling mechanism, and instead records very localised, changeable conditions.

6.1.2 Pukaki Crater

6.1.2.1 P40(T5)

pH

The assemblage across this section is dominated by alkaliphilous taxa, which account for 99% of the species present (Fig. 6.5). This level is maintained consistently for the entire length of the section, with no changes recorded across the tephra.

Salinity

Similarly, one group, fresh-brackish taxa, dominates the assemblage at 99.8%. This does not change across the tephra (Fig. 6.5).

Nitrogen Uptake

Highly nitrogen-autotrophic taxa dominate the assemblage, composing 99.3% across the section, and remain unchanged across the tephra (Fig. 6.5).

Oxygen Saturation

Diatoms requiring 'high' levels of oxygen saturation totally dominate the assemblage, accounting for 95% of the assemblage (Fig. 6.5). The high level is maintained for the entire record, except in the very first sample in the section, where 'moderate' taxa comprise 17%. No change is recorded across the tephra.

Trophic Status

Oligotrophic taxa dominate the assemblage, accounting for 95% of the population. No changes are recorded across the tephra (Fig. 6.5).

Summary

No changes in any of the autecological parameters are recorded, indicating that the influx of the T5 tephra had no impact on the environment within the lake.

P40(T5) tephra - andesitic (2 mm thick)

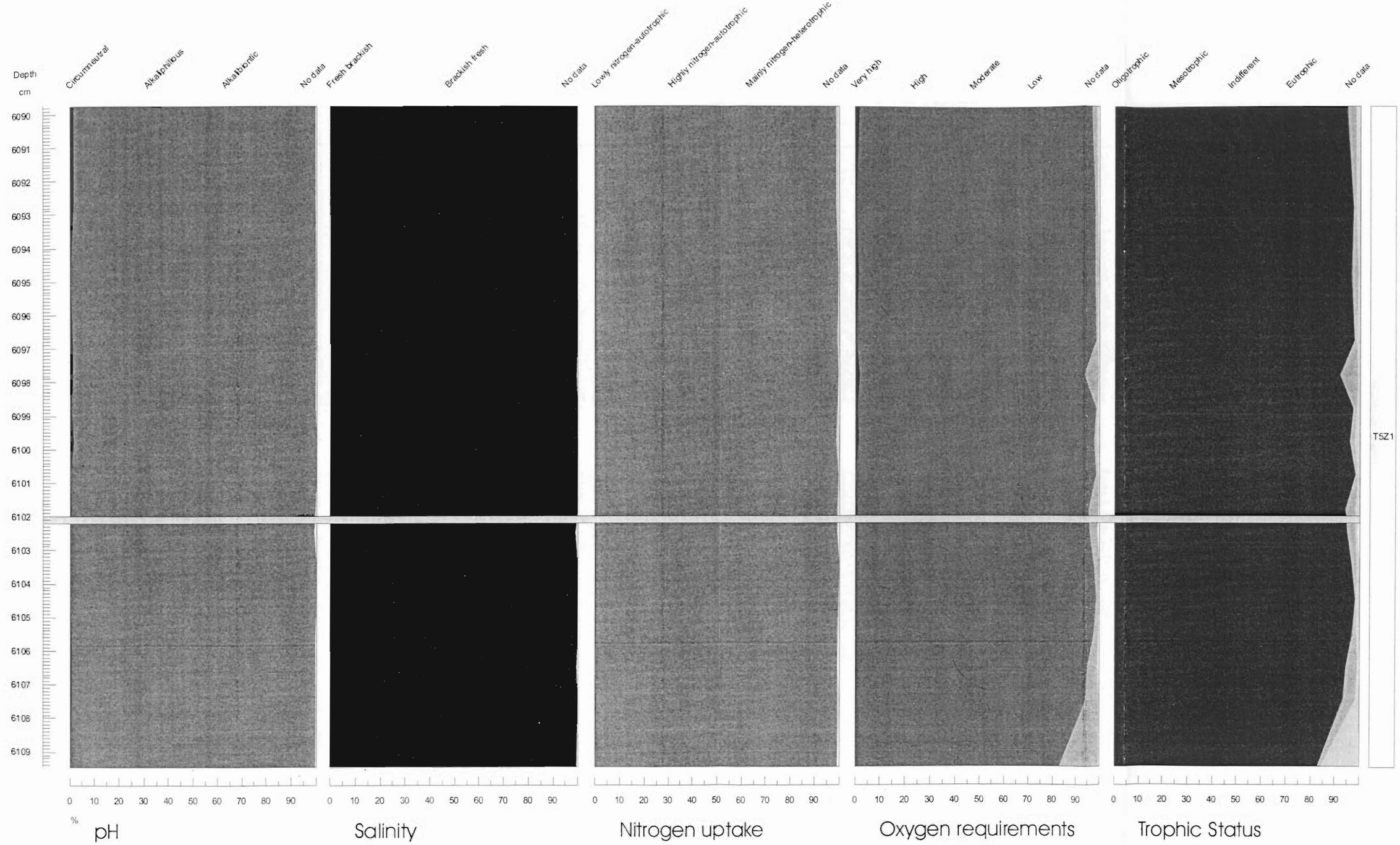


Figure 6.5: Environmental indicators across T5 tephra

6.1.2.2 P36(T6)

pH

Alkaliphilous taxa account for 98% of the assemblage within the section (Fig. 6.6). The input of the tephra at 5540 cm produces a very short-term change in the pH-indicator taxa. In pre-tephra sediments, alkaliphilous taxa comprise 99%, circumneutral 1.2%, and alkalibiontic 0.4%. However, in the sample immediately above the tephra bed, alkaliphilous taxa decrease to 86%, circumneutral taxa increase to 8%, and alkalibiontic to 3%. However, by the next sample, pre-tephra conditions have returned, with 97%, 0.5% and 0% respectively.

Salinity

Fresh-brackish taxa dominate the diatom record in the section, accounting for 99% of the count (Fig. 6.6). There is a minor fall in this group immediately above the tephra bed, lasting 12.5 cm, to 97%. This drop in marginal fresh water taxon is offset by an increase in taxa with which no salinity optima are known, so it is not known whether a genuine drop or rise in salinity occurs at this point.

Nitrogen Uptake

Within the section, high nitrogen-autotrophic taxa dominate, with this group accounting for 98% of the population (Fig. 6.6). The dominance of this group remains constant at every level sampled, except in the sample immediately above the tephra bed (at 5539.75 cm). At this depth, high nitrogen taxa drop to 85%, while low nitrogen-autotrophs increases from of 0.2% to 5%, and nitrogen-heterotrophic from 0.9% to 7%. The elevated counts of these groups do not continue past this sample; in the subsequent sample, they drop to 0.8% and 0.5% respectively, with high nitrogen-autotrophic taxa recovering to 97%.

Oxygen Saturation

Species requiring high oxygen saturation levels are the most abundant in this section, accounting for 64% (Fig. 6.6). The groups representing oxygen saturation fluctuate significantly throughout the section. Across the tephra, there is significant increase among the rarer groups, with 'very high' jumping to 8% and 'low' to 7% in the sample immediately above the tephra, whereas 'high' drops to 49%. These two groups had previously accounted for 2% and 0.3% respectively. 'Moderate' taxa

>36(T6) tephra - basaltic (<5 mm thick)

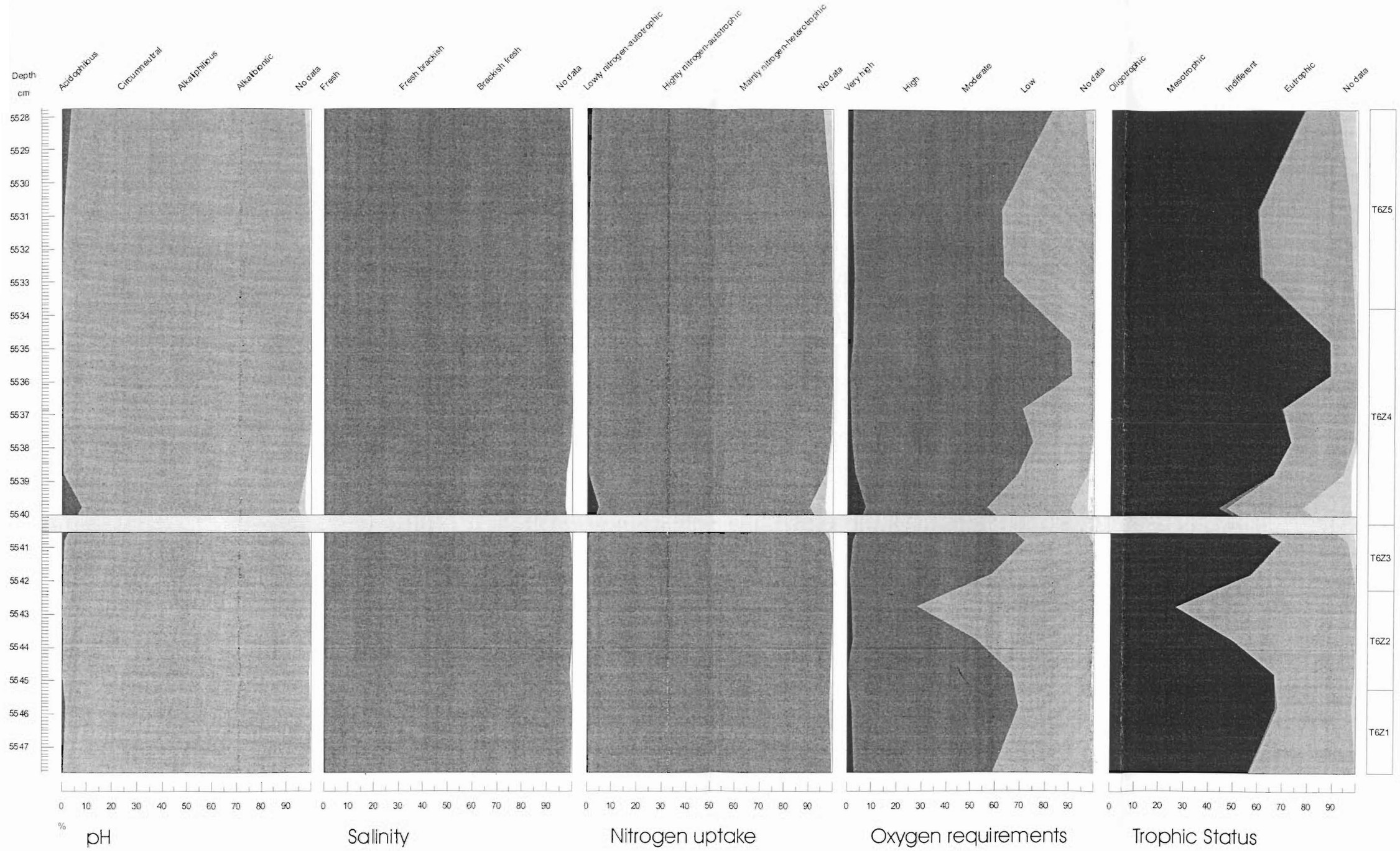


Figure 6.6: Environmental indicators across T6 tephra

remain largely unaffected across the tephra. This fluctuation does not extend past this sample, and above this depth, the dominance of 'high' taxa increases, to average 70% for the remainder of the section.

Trophic Status

Oligotrophic taxa dominate the section, with 64%, followed by indifferent taxa with 32% and eutrophic with 3% (Fig. 6.6). Immediately above the tephra, at 5539.75 cm, eutrophic taxa become prominent, increasing to 20% at the expense of oligotrophic taxa which drop to 44%. However, the rise only extends for this single depth, and continuing into post-tephra deposits, oligotrophic taxa increase their dominance, comprising up to 89%.

Summary

Short-term changes are recorded in all autecological parameters, the most noteworthy being a short-term increase in eutrophic taxa immediately following the tephra bed, followed by a gradual increase in oligotrophic taxa.

6.1.2.3 P36(T4)

pH

Alkaliphilous taxa dominate the section, making up 98% of the count (Fig. 6.7). Taxa that prefer acidic conditions of any type are completely absent, and no change is recorded across the tephra

Salinity

Fresh-brackish taxa account for 99.8% of the abundance in the section (Fig. 6.7). No change is recorded across the tephra bed.

Nitrogen Uptake

Highly nitrogen-autrophic taxa occupy the dominant population within the section, with 99% of the population, as well as 68% of all species (Fig. 6.7). The environmental indicators of nitrogen uptake do not vary across tephra.

6(T4) tephra - rhyolitic (7 mm thick)

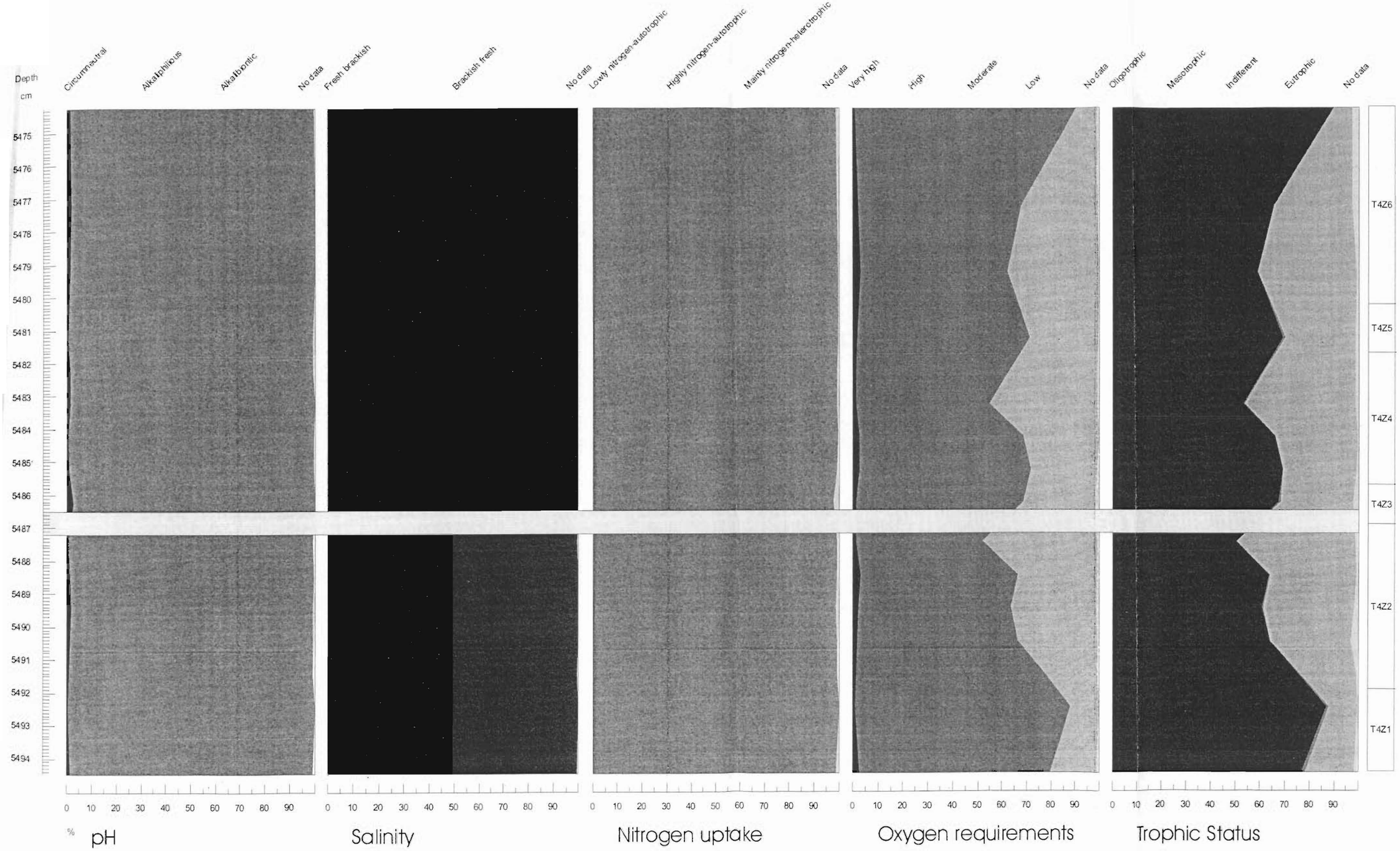


Figure 6.7: Environmental indicators across T4 tephra

Oxygen Saturation

High oxygen saturation requiring diatoms dominate the assemblage with 68%, followed 'moderate' taxa with 30% (Fig. 6.7). Fluctuations are recorded within the section, but none occur across the tephra bed.

Trophic status

The section is dominated by oligotrophic taxa, with 67%, followed by indifferent with 30% (Fig. 6.7). Again, while changes are recorded within the section, none occur across the tephra bed.

Summary

No autecological changes are recorded across the tephra

6.1.2.4 P36(T3)

pH

Alkaliphilous taxa dominate the section, accounting for 99% of the population (Fig. 6.8). No change occurs across the tephra.

Salinity

99.9% of the diatom taxa inhabiting Pukaki Crater at the time of the input of T3 tephra require fresh-brackish waters (Fig. 6.8). Only in three samples within the section are other salinity-type diatoms recorded, and no change is recorded across the tephra.

Nitrogen Uptake

Nitrogen-autotrophic taxa comprise 99% of the diatom population (Fig. 6.8). Again, no change is recorded across the tephra bed.

Oxygen Saturation

The most abundant group is 'high' species, with 67%, followed by 'moderate' species at 28% (Fig. 6.8). There is not change recorded across the tephra, instead a significant change occurs 5-10 mm above the top of the tephra. This is represented by an increase in 'high' taxa from 53% to 80%, and a drop in 'moderate' taxa from 42% to 17%. These adjusted levels are maintained for the remainder of the section.

P36(T3) - andesitic (5 mm thick)

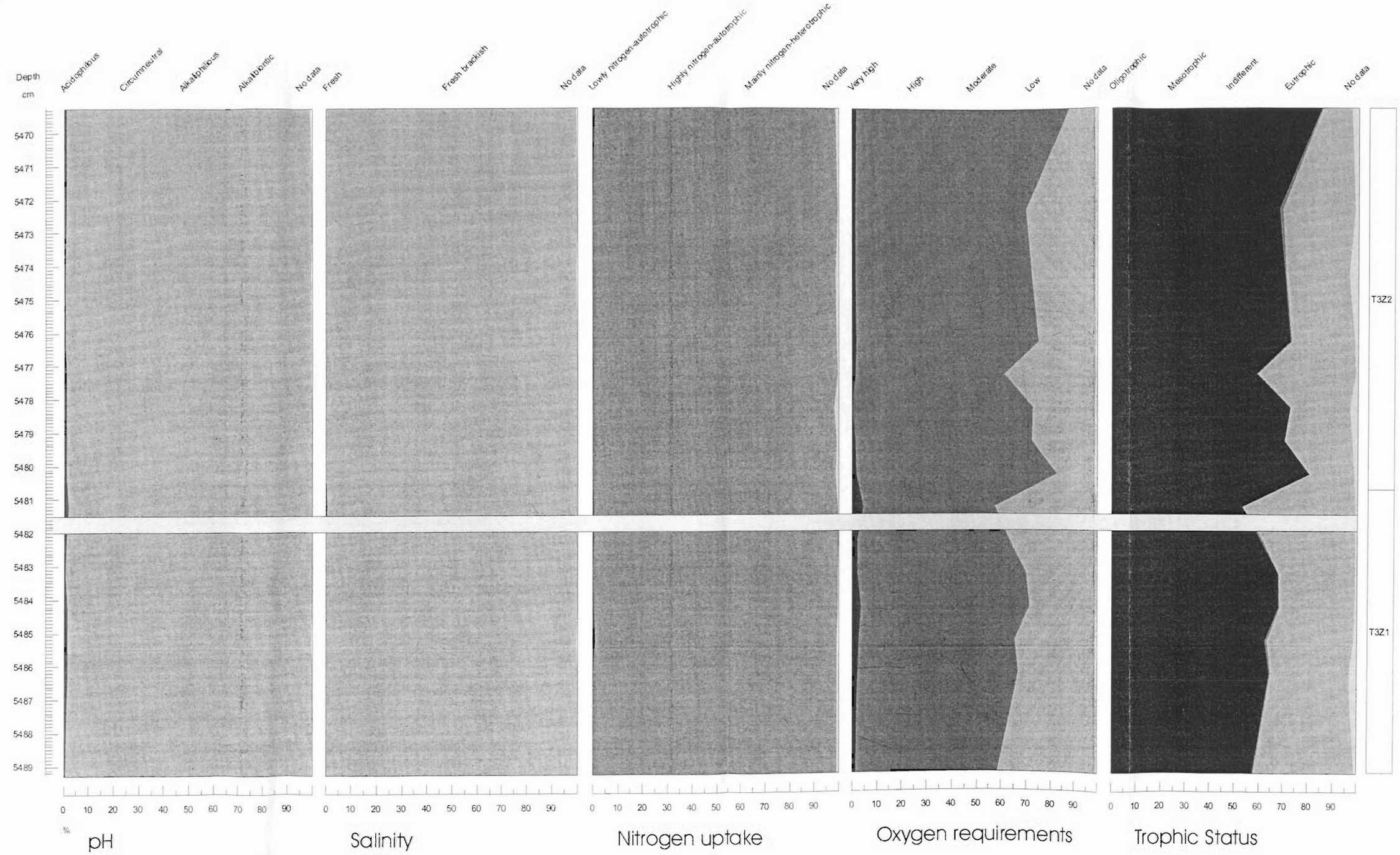


Figure 6.8: Environmental indicators across T3 tephra

Trophic Status

The section is dominated by oligotrophic taxa, which account for 67% of the total population, followed by indifferent taxa with 30% (Fig. 6.8). Again, across the tephra, no change is recorded. However, a significant shift occurs 5-10 mm above the tephra, where oligotrophic taxa jump from 53% to 80% and indifferent taxa drop from 46% to 18%. This change is maintained to the end of the section.

Summary

A significant shift in trophic state above the tephra, showing increased oligotrophic taxa dominance, is the most prominent change recorded within the autecological data.

6.1.2.5 P36(T2)

pH

Alkaliphilous taxa dominate throughout this section of Pukaki 1-01, accounting for 99% of the population (Fig. 6.9). This dominance is maintained across the tephra, comprising between 97.25% and 99.5% in all samples.

Salinity

Fresh-brackish species account for 99.7% of all taxa present in the section, and there are no changes recorded within the section (Fig. 6.9).

Nitrogen Uptake

Highly nitrogen-autotrophic taxa dominate the section (Fig. 6.9). This group makes up 99.1% of the population. Again, no change is recorded across the tephra.

Oxygen Saturation

Within the section, species which require high levels of oxygen saturation (>75%) dominate the population, averaging 72%, followed by 'moderate' with 26% (Fig. 6.9). While 'high' species remain dominant throughout the section, the relative dominance of 'high' and 'moderate' taxa vary in three zones (Fig. 6.5). Initially, from the base of the section to 5471.25 cm, 'high' species average 61% compared to 37% for 'moderate' species. This changes at 5470.25 cm, which is the sample immediately below the tephra, where 'high' taxa increase to 82% and 'moderate' drop to 16%.

P36 (T2) tephra - basaltic (200 mm thick)

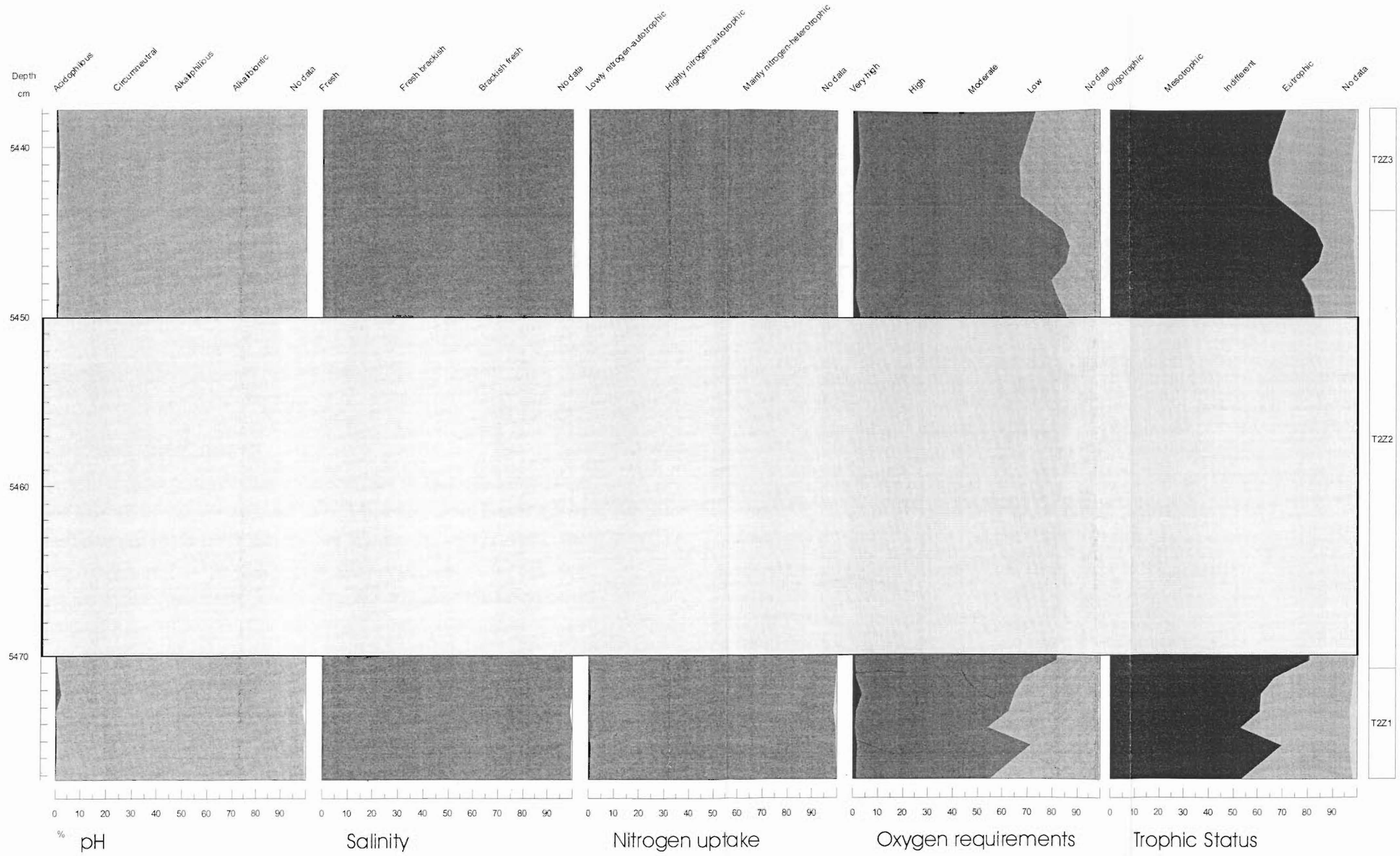


Figure 6.9: Environmental indicators across T2 tephra

This shifts again at 5444.75 cm, where 'high' drops to 67%, and 'moderate' increases to 32%. The data indicates that oxygen saturation increases slightly across the tephra bed, but not concurrent with its deposition.

Trophic Status

Two groups, oligotrophic taxa and indifferent taxa dominate the trophic status of the section (Fig. 6.9). Like the oxygen saturation record, the relative abundance of these two groups can be divided into 3 zones. In the first zone, from 5477.25 cm to 5471.25 cm, the ratio of oligotrophic taxa to indifferent species is 65:32. Then from 5471.25 cm to 5444.25 cm, it climbs to 80:18. The onset of the third zone, which continues to the end of the section, is characterised by a decrease in oligotrophic taxa, so the ratio drops to 67:30.

Summary

The most important information produced from this section is that there are major changes recorded across the section, however, they pre-date tephra input.

6.1.2.6 Pukaki Crater summary

The records from Pukaki Crater show a lake dominated by *Cyclotella stelligera* and *Synedra ulna* and its varieties. These two taxa never account for less than 97% of the assemblage in any section. This indicates very low diversity within the lake. The conditions appear stable for the duration of the sections analysed, with no significant environmental perturbations being recorded. Salinity does not fluctuate, signifying that Pukaki Crater remained a fresh water lake. Similarly, pH remains slightly alkaline, indicating a pH of just above 7.0. Likewise, nitrogen indicators remain unchanged, indicating low availability of organic nitrogen compounds. Oxygen saturation does record some variability within the lake, but not of any significance. Trophic status, similarly, does vary but oligotrophic conditions dominate. This shows that the lake had very low levels of dissolved organic nutrients throughout the period from 61 m to 54 m.

6.1.3 Summary

Seven out of nine sections record some changes in autecological indicators across the tephras, with the most significant result being that 5 out of the 9 diatom assemblages record a shift towards oligotrophic conditions following the tephra input. Of the remaining sections, one records a very short-term increase in eutrophic taxa followed by an increase in oligotrophic taxa, while the other section records an increase in indifferent taxa at the expense of eutrophic taxa, with oligotrophic species remaining onstant. The cause of these events is discussed in Chapter 7.

6.2 *Sediment Geochemistry*

6.2.1 Introduction

Sediment geochemistry analysis was conducted on a number of samples in an attempt to gain a clearer understanding of the results produced by the diatom species data and environmental indicator data. Three tephra sections were analysed; all chosen from the Lake Pupuke core. The majority of samples analysed were collected across the Rangitoto tephra, which was selected because significant changes in both the species and environmental data are recorded. Additionally, the Tahua tephra was chosen because it also documents changes within the section, and as in the Rangitoto samples, the changes do not occur contemporaneous with the tephra bed. The final tephra analysed, the Rotoma, was sampled as an experimental blank because no significant changes were recorded in the section. Samples were taken from each diatom zone in the case of the Rangitoto and Tahua tephras and arbitrarily above and below the tephra for the Rotoma. Ten elements were analysed by this procedure: silica, phosphorus, iron, aluminium, titanium, manganese, magnesium, calcium, sodium and potassium, which are all represented as oxides.

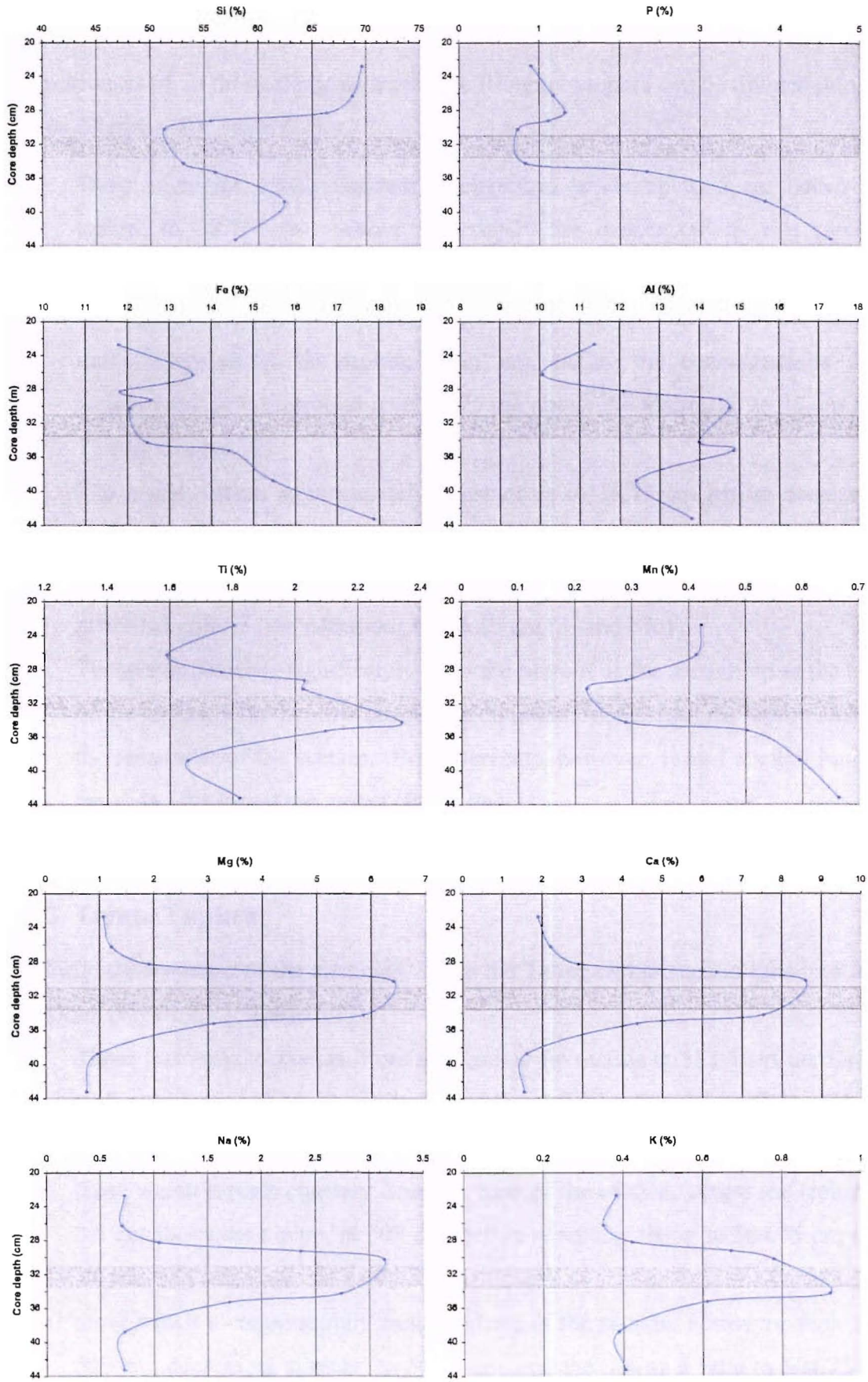


Figure 6.10: Sediment geochemistry across Rangitoto tephra

6.2.2 Rangitoto tephra

The responses of all these elements across the Rangitoto tephra can be divided into 3 groups (Figure 6.10; Table 6.1):

1. Those elements which maintain background levels up to 5 cm below the tephra, to 38.75 cm. Above this depth, the concentrations rise rapidly, reaching levels up to 5 times background concentrations immediately below the tephra, at 34.25 cm. These high levels are maintained to the sample immediately above the tephra, 30.25 cm, before the concentrations drop rapidly back to background levels 4.75 cm above the tephra, at 26.25 cm (Al, Ti, Mg, Ca, Na, K).
2. Those that remain approximately constant up to 38.75 cm before decreasing up to the base of the tephra. This low concentration is continued to immediately above the tephra before the elements increase rapidly, regaining near-background concentrations by 26.25 cm (Si and Mn).
3. Those that decrease significantly from the bottom of the section up to the base of the tephra, with this low concentration maintained across the tephra and for the remainder of the section. Both elements, however, record a small jump 2 cm above the top of the tephra (P and Fe).

6.2.3 Tahua Tephra

Similarly, the response of the elements within the Tahua tephra section falls into four categories (Figure 6.11; Table 6.1)

1. Those that remain constant from the base of the section at 512.5 cm, across the tephra through to 3 cm above the top of the tephra, at 506.25 cm, before rising rapidly to 504.75 (Fe);
2. those which remain constant from the base of the section, across the tephra to 0.5 cm above the tephra, at 509 cm, before gradually rising to 504.75 cm (Al, Ti, Mn, Mg and Ca);
3. those which increase rapidly from the base of the section, across the tephra to 509 cm, decreasing slightly to 506.5 cm, and the rising a little to 504.75 cm (Na and K);

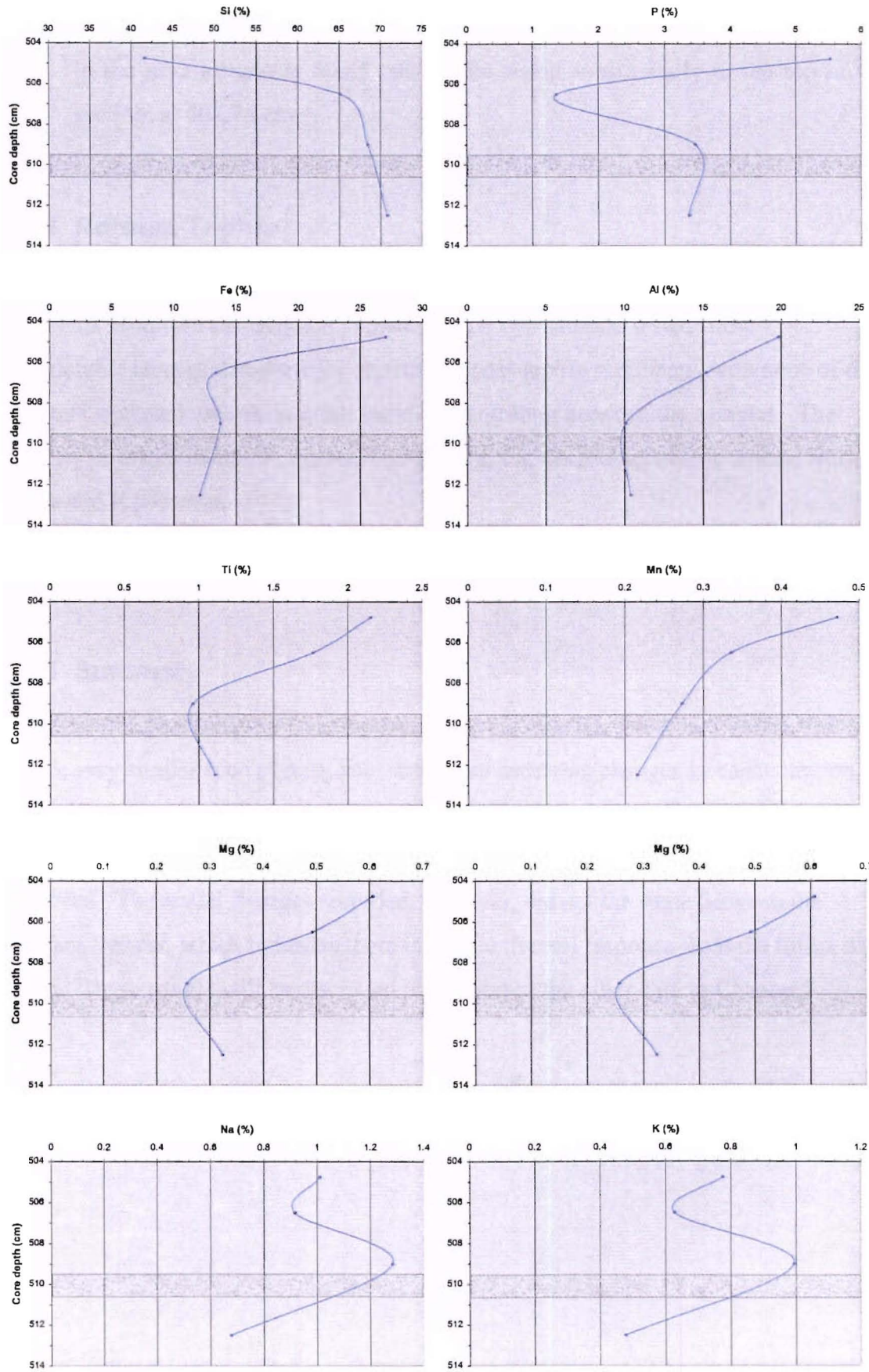


Figure 6.11: Sediment geochemistry across Tahua tephra

4. P, which remains unchanged across the tephra bed, to 509 cm, then decreasing to the next sample at 506.5 cm, before rising substantially to the top of the section, at 504.75 cm

6.2.4 Rotoma Tephra

Only two samples were taken from across the Rotoma tephra (Table 6.1). Therefore, the results produced are minimal. However, the two samples tested show considerable changes between pre-tephra and post-tephra sediments, with none of the elements analysed maintaining the same concentration between the samples. The majority of the elements: P, Fe, Al, Ti, Mn, Mg, Ca, decline across the tephra, while Si, Na and K increase.

6.2.5 Summary

The sediment geochemistry record preserved across the Rangitoto and Tahua tephras show a very similar type of response, in that the dominant changes in concentration of the various elements coincide with the depths where the significant changes are recorded in the diatom assemblage data, and not where the tephra is currently preserved. The actual changes recorded, however, are not the same between the different tephras, which indicates there is not a universal response from the influx of tephra. These results will be discussed in relation to the other data in Chapter 7

Table 6.1: Sediment geochemistry data expressed as percentages

	depth	SiO_2	P_2O_5	Fe_2O_3	Al_2O_3	TiO_2	MnO	MgO	CaO	Na_2O	K_2O	Total
Rangitoto	22.75	69.66788251	0.902284508	11.78729123	11.36494529	1.804569015	0.42234594	1.075062392	1.900556729	0.729506623	0.383950854	100.0383951
"	26.25	68.74741629	1.178172799	13.55932203	10.06614303	1.591566763	0.413393964	1.219512195	2.21165771	0.70276974	0.35138487	100.0413394
"	28.25	66.3788352	1.322799927	11.83171045	12.10729377	1.763733235	0.330699982	1.910711005	2.90281095	1.047216608	0.422561088	100.0183722
"	29.25	55.60640732	1.113653699	12.5553013	14.52326468	2.028985507	0.289855072	4.500381388	6.361556064	2.36460717	0.671243326	100.0152555
"	30.25	51.29129828	0.732899023	12.05211726	14.751047	2.024197301	0.221033039	6.40995812	8.608655188	3.140995812	0.779432294	100.0116333
"	34.25	53.03509979	0.825877495	12.47075017	13.98485891	2.339986235	0.289057123	5.849965588	7.543014453	2.739160358	0.922229869	100
"	35.25	55.99475868	2.33675475	14.41362743	14.85040402	2.096527626	0.502293077	3.10111378	4.367765888	1.703428696	0.611487224	99.97816117
"	38.75	62.40932642	3.808290155	15.46632124	12.40932642	1.658031088	0.595854922	0.958549223	1.606217617	0.725388601	0.388601036	100.0259067
"	43.25	57.83689994	4.626951995	17.87160208	13.79410064	1.821862348	0.665124349	0.751879699	1.532677848	0.722961249	0.4048583	100.0289184
Tahua	504.75	41.57681941	5.525606469	27.02156334	19.81132075	2.156334232	0.471698113	0.606469003	1.078167116	1.010781671	0.774932615	100.0336927
"	506.5	65.11627907	1.364042934	13.37209302	15.20572451	1.766547406	0.335420394	0.491949911	0.805008945	0.916815742	0.626118068	100
"	509	68.44130853	3.46375882	13.71071199	10.03848621	0.962155228	0.272610648	0.256574727	0.577293137	1.282873637	0.994227069	100
"	512.5	70.81730029	3.370786517	12.0671079	10.35862706	1.108203786	0.21548407	0.323226104	0.600277051	0.677235647	0.477143297	100.0153917
Rotoma	570.5	70.10377203	0.263548015	8.450008236	14.24806457	0.576511283	0.164717509	0.280019766	0.971833306	2.750782408	2.190742876	100
	578.25	43.47294405	2.231733415	28.52338734	20.02445735	2.048303271	0.336288597	0.611433812	1.161724243	0.917150718	0.672577194	100

Chapter seven: Discussion

7.1 *Introduction*

In Chapters 5 & 6, it is shown that seven of the nine sections analysed in this project record changes across the tephra bed. The sections can be separated into four categories based on the apparent responses:

1. The physical properties of the tephra produces changes in the diatom assemblage,
2. A shift in the variety of *Synedra ulna*,
3. A delayed response to reduced nutrient levels in the lake waters, and
4. No change recorded.

These mechanisms will be discussed below.

7.2 *Physical effects of tephra deposition*

Two sections record impacts produced by the physical effects of the influx of tephra into a lake, however, the exact responses are different, and this appears to be related to the diatom assemblages inhabiting the lake at the time of tephra input.

7.2.1 The suppression of benthic taxa

7.2.1.1 Rotoma tephra

The section across the Rotoma tephra records the highest level of benthic taxa, and the highest amount of variability in terms of dominant species of any of the sections analysed (Fig. 7.1). No single taxon dominates the assemblage; instead, three taxa are prominent: *Fragilaria pinnata*, *Synedra ulna*, and *Cyclotella stelligera*. Clear patterns are difficult to extract from the record because of the high variation in the abundances of these prominent taxa and the autecological data, most extensively, above the tephra. However, there is a short zone (RoZ2) above the Rotoma tephra where the

relative frequencies of *F. pinnata* and *C. stelligera* are reversed. The onset of this zone is coincidental with the tephra. Because *F. pinnata* is benthic and *C. stelligera* is planktonic, this shift cannot be a function of direct taxonomic replacement.

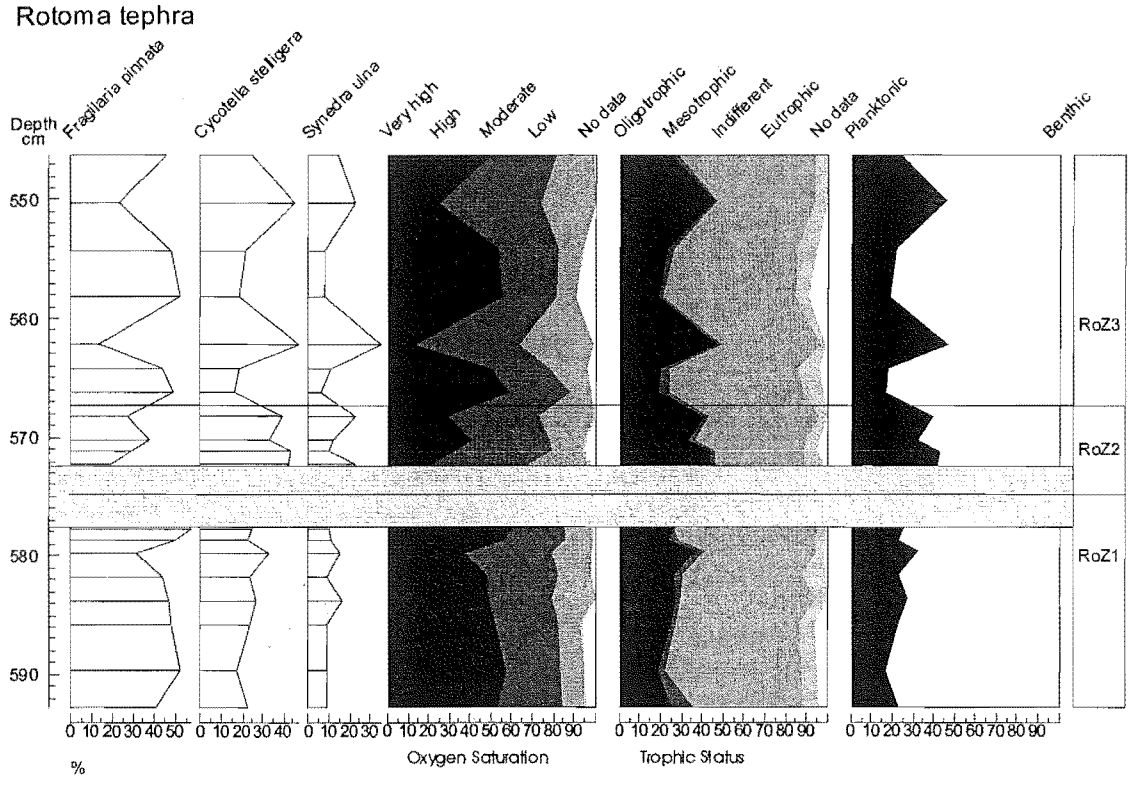


Figure 7.1: Selected results from Rotoma tephra section

Rotoma Zone 2 is difficult to identify within the autecological data, with the input of 50 mm of rhyolitic tephra having little effect on the environmental conditions in the lake (Fig. 7.1). This zone is not apparent within the pH, salinity or nitrogen indicators. The data indicates that the pH of the lake was slightly above 7.0, the salinity is representative of a fresh water lake containing low levels of organically-bound nitrogen compounds. There are, however, large-scale variations recorded in both oxygen saturation and trophic status. A significant reduction in oxygen saturation is recorded immediately above the tephra, which could indicate that influx of the tephra reduced oxygen availability on the bottom of the lake.

RoZ2 is most readily identifiable within the trophic record, with an increase in oligotrophic conditions into RoZ2. However, the dominant trophic class within the section is indifferent taxa, which have no recorded preference for trophic conditions. As the increase in oligotrophic taxa is at the expense of indifferent taxa while eutrophic taxa are unaffected, RoZ2 probably does not represent a true change in trophic state. This is confirmed when the assemblage is divided up into planktonic

and benthic taxa. The planktonic habitat is dominated by oligotrophic taxa, at 99%, whereas in benthic habitats, indifferent taxa are the key group at 85%, with oligotrophic taxa <1%. Across the tephra, the only notable change is that benthic eutrophic taxa increase from 8% to 11% in RoZ2. This indicates that a significant trophic shift is not produced by the influx of the Rotoma tephra, and instead, some other mechanism was responsible for the short-term decline in *F. pinnata* in RoZ2.

Tephra settling on the bottom surface of a lake can have potentially disastrous consequences on benthic habitats of diatoms. The most significant of these is the smothering of the sediment surface and burying of the diatoms. As well as submerging the diatoms directly, tephra would submerge waterweeds, which would detrimentally affect epiphytic taxa, such as *F. pinnata*. In addition, tephra particles, principally pumice, could become trapped in the shoots of the waterweeds and shade the underlying diatoms, restricting photosynthesis (e.g. Harper *et al*, 1985). The main impact on the planktonic habitat of *C. stelligera* would be increased turbidity, and lessened turbulence due to tephra particles in the water column. This would have little effect on *C. stelligera* because their frustules are light, with low concentrations of silica, which has a high specific gravity. Therefore, it does not require high levels of turbulence to remain afloat (Telford, 1998).

The impact on benthic taxa continues 5 cm up the core. Based on broad sedimentation rates determined from the core depths and the ages of the recorded tephras (Table 7.1), the duration of RoZ2 is estimated at 125 years. This is substantially longer than the several years predicted by Edmondson (1984) for the duration of physical effects of tephra on benthic habitats in Canadian lakes, but is significantly shorter than the 300 years suggested by Harper *et al* (1986) in Lake Poukawa, New Zealand.

Table 7.1: Sedimentation rates for Lake Pupuke

Tephra	Depth (cm)	Approximate age	Sedimentation rate (cm/yr)
Rangitoto	31	620	
			}0.13
Taupo	181	1800	
			}0.07
Tahua	509.5	7000	
			}0.03
Rotoma	572.5	9500	
Mean rate of sedimentation			0.06

This type of response to tephra input is not recorded elsewhere in either the Lake Pupuke or the Pukaki Crater cores. This is because benthic diatoms are rare in the other assemblages. The preponderance of benthic taxa in this section could indicate that the lake was shallower then than at any later stage.

7.2.2 Differential planktonic/benthic effects

7.2.2.1 Taupo tephra

The section across the Taupo tephra records a high level of variation in the diatom assemblage. No major changes occur across the 65 mm Taupo tephra (Fig. 7.2), with *Cyclotella stelligera* and *Aulacoseira ambigua* the dominant species. There is, however, a short-term (30 mm) decline in *A. ambigua* 0.75 cm above the tephra (TpZ3), which correlates to an identical rise in *Synedra ulna* during the same interval (180.25 cm - 177.25 cm). The end of zone TpZ3 is marked by a return to conditions present at the end of TpZ2.

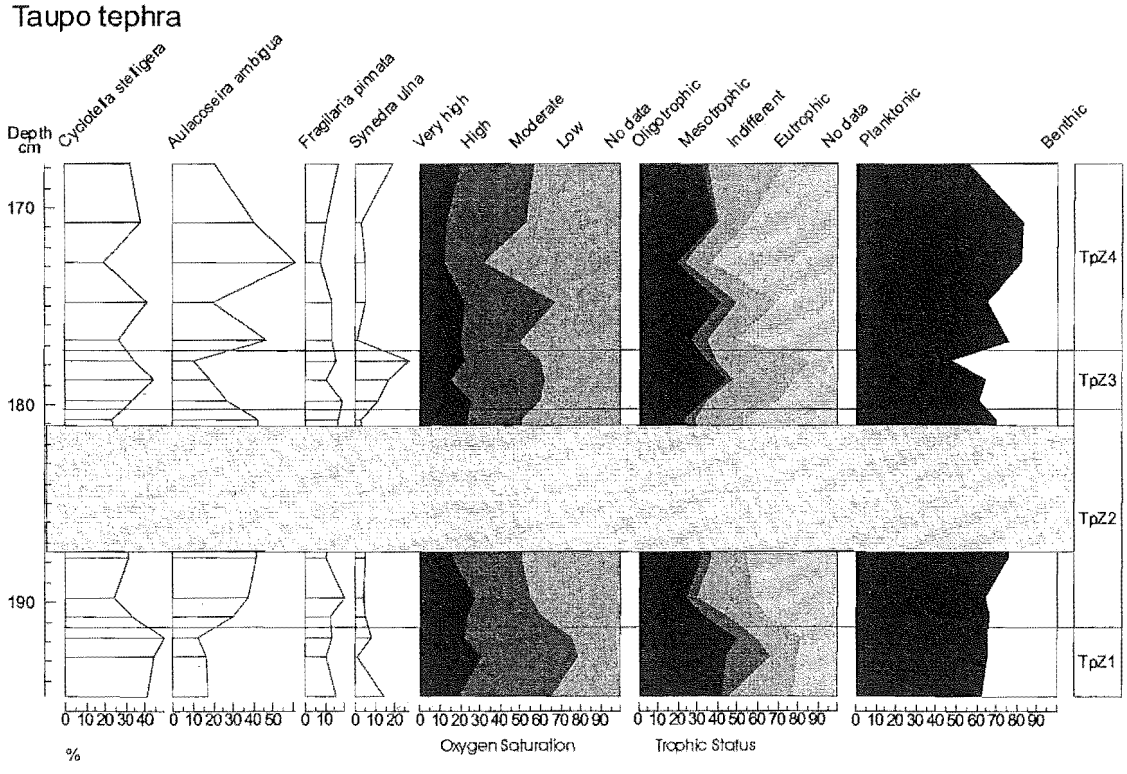


Figure 7.2: Selected results from Taupo tephra section

The autecological data show no distinct changes across the tephra, or indeed across the entire section (Fig. 7.2). Throughout the section, Lake Pupuke was a freshwater lake, with a pH of slightly above 7.0, low in organic nitrogen compounds, with high

but variable levels of oxygen saturation. Minor changes in trophic status do occur in zone TpZ3, with a reduction in eutrophic taxa, and increase in indifferent taxa. The record preserved by benthic diatoms indicates a habitat dominated by indifferent taxa, while the planktonic habitat is dominated by oligotrophic taxa, but with eutrophic taxa also prominent. It is unusual for two trophic groups representing different ends of the trophic spectrum to be so well represented within a single record. The large degree of variation and spread between the different trophic states indicates that the nutrient conditions within the lake was not a limiting factor on the diatom assemblage, and did not play a significant role in determining the composition of the diatom assemblage. Additionally, in TpZ4, after the effects of the tephra influx have waned, there is a large level of variability recorded in the trophic indicators. This could represent a destabilised environment in terms of nutrient availability following the tephra input, which could be produced by an extended period of in-wash of nutrients from tephra within the catchment. The duration of in-wash of residual nutrients would have to be in the vicinity of 70-100 years based on sedimentation rates on top of the duration of the direct impact of 75 years. This is realistic given the thickness of the tephra bed and the small catchment of the lake.

The influx of the Taupo tephra at 181 cm appears to produce no significant effect on the environmental conditions within the lake. The ratio of benthic to planktonic taxa remains stable across the tephra, which appears to indicate that physical effects of the tephra did not preferentially affect any specific habitat. Therefore, some additional mechanism appears to be responsible for the response recorded in TpZ3. Several processes may be to blame for the decline in *A. ambigua* and the corresponding rise in *S. ulna*. Decreased turbulence related to the large number of tephra particles present in the water column could explain the decrease in *A. ambigua*, because the heavy frustules require turbulent waters to remain afloat (Telford, 1998). Additionally, tephra particles can become trapped in the filaments of the large *A. ambigua* frustules, pushing the individuals down to the lake bottom, becoming buried in the sediment (M. Harper, pers. comm., 2003). As the Taupo tephra is rhyolitic, it is less dense than other tephras, so therefore would remain in suspension for longer, facilitating such an impact. This does not explain the rise of *S. ulna*, which is benthic. If *A. ambigua* was buried in the tephra, then it is probable that *S. ulna* would also become buried by the settling tephra, as the Taupo tephra is the thickest tephra recorded in the Lake Pupuke core. However, as Taupo tephra is a low density, small

grained tephra, the difficulty for benthic diatoms to burrow through the tephra to the new sediment-water interface is lessened. Therefore, it is possible that *A. ambigua* was impaired by decreased turbulence and tephra trapped in the frustule filaments, while *S. ulna*, along with the other prominent benthic taxa present, *Fragilaria pinnata*, were able to migrate through the less dense tephra particles to the top of the tephra.

The record indicates that the abundance of *F. pinnata* was unaffected by the tephra, while *S. ulna* increased significantly. This could be related to the principle habitat which *F. pinnata* inhabits, waterweeds. If the waterweeds become partly submerged by the settling tephra, until such time as they completely regenerate, the population of epiphytic diatoms, such as *F. pinnata*, will be restricted (e.g. Harper *et al*, 1986). Therefore, the responses recoded in both planktonic and benthic habitats appear to be produced by physical properties of the settling tephra.

7.3 *Synedra ulna variety fluctuations*

Synedra ulna occurs as two forms; *Synedra ulna* and *Synedra ulna* v *spathulifera*, however, *S. ulna* v *spathulifera* does not occur in Lake Pupuke. In Pukaki Crater, *Synedra ulna* v *spathulifera* is recorded commonly in 3 of the 5 sections. These two taxa appear to be mutually exclusive. In two of the sections, around T6 and T4, the input of the tephra reduces the abundance of *S. ulna* v *spathulifera* relative to *S. ulna*.

7.3.1 P36(T6) tephra

The basaltic T6 tephra has not been correlated to known tephra or source volcanoes within the Auckland Volcanic Field, so the exact age of the tephra is unknown. However, based on stratigraphic position, and taking an average sedimentation rate within Pukaki Crater of 0.02 cm/yr (Sandiford *et al*, 2001), an approximate age of 25000 yrs B.P. is obtained.

The diatom assemblage records multiple fluctuations within the 20 cm section (Fig. 7.3). The dominant taxon across the section is *Cyclotella stelligera*, however, the majority of the variation present within the section is recorded by two taxa: *Synedra ulna* v *spathulifera* and *Synedra ulna*. Zone T6Z4, which begins at the top of

the tephra bed, as well as recording the replacement of *S. ulna* v *spathulifera* by *S. ulna*, also records a major increase in the abundance of many rare benthic species. Taxa such as *Cocconeis placentula*, *Gomphonema parvulum*, *Fragilaria pinnata*, *Epithemia sorex*, *Nitzschia* spp., *Cymbella affinis* and *Epithemia adnata* increase too at least 300% times their background level, suggesting that the tephra produced optimum environmental conditions on the lake bottom. This pattern does not continue above this depth, with the majority of these taxa returning to pre-tephra levels in the next sample. Therefore the duration of the impact was very short, a maximum of 50 years. Species diversity in this sample also increases, with 21 species present out of the total count of 29, compared to 15 taxa in the next most diverse sample, at 5527.75 cm.

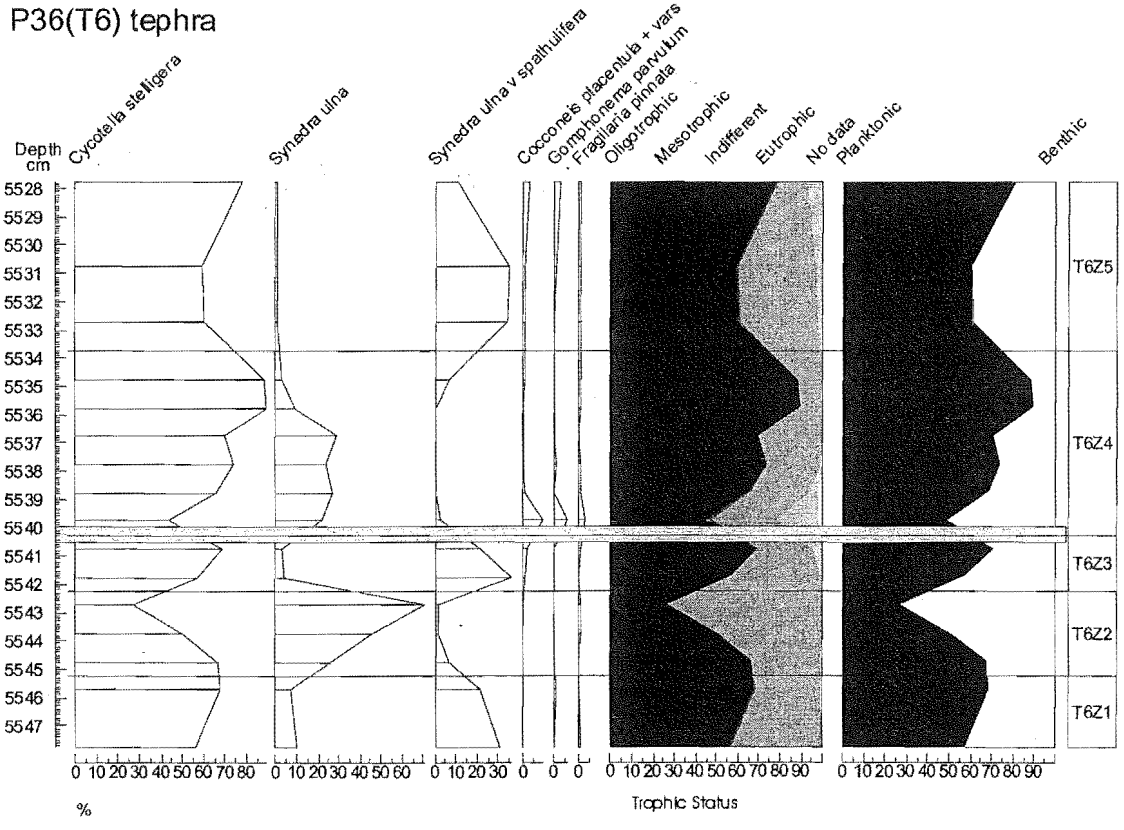


Figure 7.3: Selected results from T6 tephra section

The autecological data across the T6 tephra also records this change immediately above the tephra, by a slight reduction in pH (Fig. 7.3). Nitrogen uptake indicators undergo similar changes, although as both high nitrogen and low nitrogen conditions increase, nitrogen availability does not appear to be a limiting factor within the lake, nor oxygen availability. The most significant change occurs with regard to trophic status, which an increase in eutrophic taxa from 3% to 20%, at the expense of

oligotrophic taxa. This suggests increased nutrient levels within the lake; however, as the majority of assemblage change is recorded in benthic taxa, the impact appears to be restricted its effects to benthic taxa, with the planktonic environment remaining unaffected.

7.3.2 P36(T4) tephra

By the use of geochemical analysis, T4 can be correlated to the Kawakawa tephra, erupted from the Taupo Volcanic Centre c. 22500 yr B.P. (Froggatt & Lowe, 1990).

Cyclotella stelligera dominates the diatom assemblage throughout the section, and undergoes no changes across the 7 mm tephra (Fig. 7.4). There are however, significant fluctuations recorded in the relative abundances of *Synedra ulna* v *spathulifera* and *Synedra ulna*. The tephra is marked by the disappearance of *S. ulna* v *spathulifera* from the assemblage, and the increase of *S. ulna* from 9% to 29%, with this pattern of response to the tephra input being repeated at 5481.25 cm, in T4Z5. Two rare taxa, *Achnanthes minutissima* and *Nitzschia* spp. also disappear with *S. ulna* v *spathulifera*.

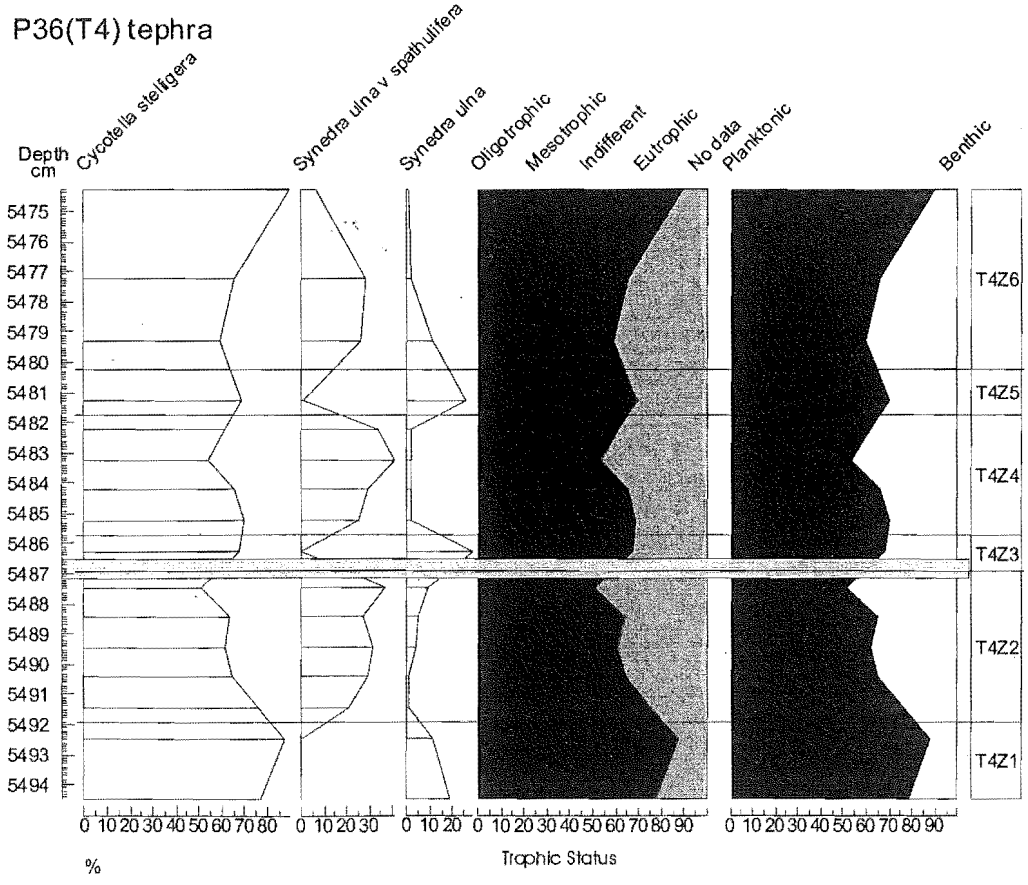


Figure 7.4: Selected results from T4 tephra section

The autecological data shows no changes across the diatom zones. This indicates that *S. ulna* and *S. ulna* v *spathulifera* have the same environmental preferences for all the indicators tested by this method.

7.3.3 Impact of the tephra and mechanisms of response

While T6 and T4 both record changes in the diatom assemblage across the tephra, the impact of the tephra on the lake environment does not appear to be consistent between the sections. In the T6 section, the tephra appears to have caused a short-term eutrophication of the lake bottom. This is most likely a response to the dissolution of nutrients from the tephra, which enabled eutrophic benthic taxa (e.g. *Cocconeis placentula*, *Gomphonema parvulum*, *Fragilaria pinnata*, *Epithemia sorex*, *Nitzschia* spp., *Cymbella affinis* and *Epithemia adnata*) to become prominent for a short time. Another possibility is that the tephra affected the dominant benthic taxa (*S. ulna* and *S. ulna* v *spathulifera*) negatively, thereby opening up ecological niches that these rare taxa occupied. However, this is unlikely because the combined counts of *S. ulna* and *S. ulna* v *spathulifera* remain constant across the tephra, and the planktonic taxa, *C. stelligera* decreases. This indicates that the benthic taxa increased relative to the planktonic species, and that the drop in *C. stelligera* is more associated with the increase in benthic taxa impacting on the representation of *C. stelligera* within the count, opposed to an actual reduction in abundance. This may indicate that *S. ulna* v *spathulifera* has slightly higher nutrient requirements than *S. ulna*, although the relationship cannot be this straightforward because when oligotrophic conditions become dominant above this level, *S. ulna* v *spathulifera* remains dominant over *S. ulna*.

The section across T4 tephra, while also recording a reduction in *S. ulna* v *spathulifera* and increase in *S. ulna*, does not suggest enhanced eutrophic conditions in benthic habitats immediately above the tephra. Instead, the impact of the tephra is solely felt by *S. ulna* v *spathulifera* and *S. ulna*. The impact of the tephra on these two taxa is not known. However, the relationship between *S. ulna* and *S. ulna* v *spathulifera* appears to be one of simple taxonomic replacement. This indicates that the environmental requirements of these two taxa are very similar. Generally, high levels of heavy metals and other pollutants are believed to be the primary cause of the formation of teratological diatom forms such as *S. ulna* v *spathulifera* (e.g.

MacFarland *et al*, 1997). However, the record shows the opposite pattern. Within Pukaki Crater, the only likely sources of such elements would be from dissolution of the tephra, or seepage from underlying sediments, which could be blocked off by the deposition of the tephra. This suggests that either the teratological form is not the result of heavy metal pollution, or that the lake was high in these elements throughout the length of core between 54 m - 55 m depth, although, the other taxa do not indicate high levels of pollutants within the lake.

The significant outcome from the identification of *S. ulna* v *spathulifera* in the Pukaki Crater core is its relationship with *S. ulna*, and the response to the influx of the T4 tephra. The same pattern recorded across T4 is seen again 5 cm above, at 5481.25 cm. This depth is present across the T3 tephra (see section 7.4.3), and represents the depth where the T3 tephra is preserved. This provides the possibility that the response of *S. ulna* v *spathulifera* and *S. ulna* could be used as a predictive tool for the identification of tephra within sediment cores. However, the response of the diatom assemblage across this tephra in the two sections is not comparable. The prediction is based on the replacement of *S. ulna* v *spathulifera* by *S. ulna*; however, this relationship is not recorded across in the T3 section. The replacement of *S. ulna* v *spathulifera* by *S. ulna* is also recorded at another level within the T4 section, at 5491.95 cm; however, no tephra is either preserved or recorded at this depth. This suggests that the relationship between these two species and tephra input is not as straightforward as previously suggested.

7.4 *Delayed response to tephra influx*

The most significant response to the tephra flux into the lake environments is a reduction in nutrient levels following tephra input. This response is recorded across three tephras. The response of the diatoms, however, do not appear to be instantaneous, with an offset recorded between the depths where the tephra is currently preserved and where the change in the diatom assemblage and sediment geochemistry is recorded.

7.4.1 Rangitoto tephra

There are major changes in the diatom assemblage recorded in the section that contains the Rangitoto tephra (Fig. 7.5). The first change occurs 3.75 cm below the tephra, while the more significant occurs 1.75 cm above the tephra. RgZ1 is dominated by *Aulacoseira ambigua*, followed by *Stephanodiscus* species. *A. ambigua* remains the dominant taxa in RgZ2, however, its abundance drops significantly, and several other taxa, including *Synedra ulna*, *Fragilaria pinnata*, *Fragilaria crotonensis* and *Cyclotella stelligera* become prominent. Sponge spicules are present in RgZ2 in abundances that suggest an increase in supply of finer sedimentary particles to the lake (M. Harper, pers. comm., 2003). Zone RgZ2 extends through the tephra to 29.25 cm (1.75 cm above the tephra). The onset of RgZ3 is characterised by a dramatic increase in *C. stelligera*, which jumps from 20% at the end of RgZ2 to 81% in the first sample in RgZ3, while the populations of almost all other diatom species present decrease significantly; *A. ambigua* slips to only 5% of the total, *S. ulna* to 2%, *Stephanodiscus* spp. to less than 1%, *F. pinnata* drops slightly to 3% and *F. crotonensis* disappears from the lake altogether. Additionally, several rarer species become prominent in RgZ3, most notably *Fragilaria minutissima*, and there are numerous taxa which are only present in RgZ3, including *Achnanthes exigua* v *elliptica*, *Rhopalodia novae zealandiae*, *Mastogloia elliptica*, *Pinnularia* spp., *Eunotia* spp., and *Achnanthes lanceolata* v *frequentissima*. The consistent occurrence of these rare taxa throughout RgZ3 implies that their presence is related to a change in conditions at the beginning of RgZ3, and not a product of the counting regime.

All the environmental indicators record changes across the section, with the most significant response being that of trophic state (Fig. 7.5). The autecological zones are equivalent to the diatom assemblage zones in both timing and duration. Across the change at 29.25 cm, pH dropped slightly, salinity remains unchanged, nitrogen availability decreased, as did oxygen saturation. The most striking result is for trophic status, which unlike the other autecological variables analysed records changes of similar timing, duration and scale to those recorded by the diatom assemblage data. This indicates that trophic status was the principal limiting factor in Lake Pupuke at the time of the influx of the Rangitoto tephra. In RgZ1, the lake was eutrophic, but into RgZ2, the nutrient status became more variable, with oligotrophic, mesotrophic and indifferent taxa all prominent. An instantaneous loss of the nutrients, signified by

an upsurge in oligotrophic taxa, marks the onset of RgZ3, with a correspondingly rapid decline in all other trophic groups.

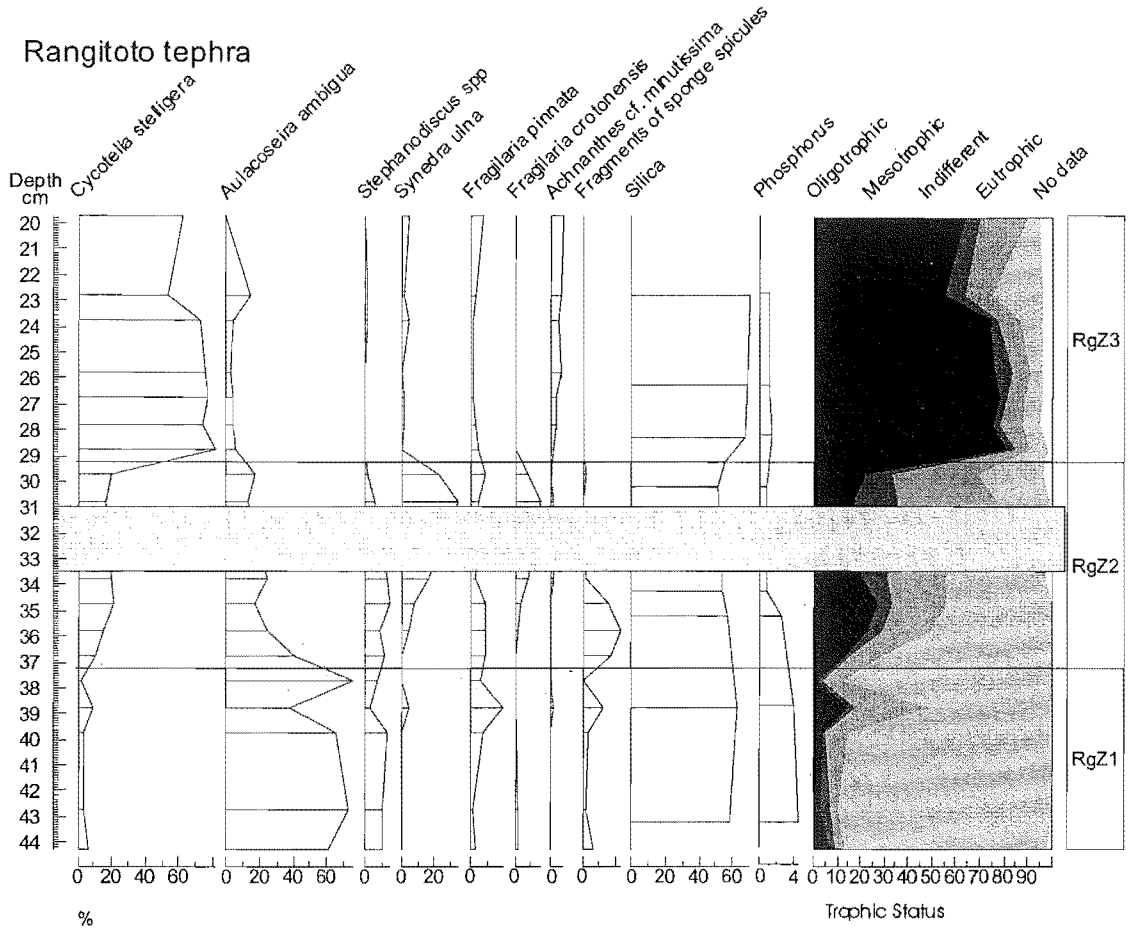


Figure 7.5: Selected results from Rangitoto tephra section

High-resolution sediment geochemistry analysis was undertaken across the Rangitoto tephra section. This data shows trends strikingly similar to those present in the diatom results (Fig 7.5). In terms of the timing and duration, the sediment geochemistry data illustrates shifts in the levels of the various elements at the same depths as changes recorded in the diatom assemblage and the autecological data. The elements that are of special interest, Si and P, show very different reactions within the section, but what is common throughout the elements analysed, is that the area of activity extends much wider than the zone of the tephra, stretching from 4 cm below the tephra to 2 cm above. While down-washing of nutrients is common, upward mobility of chemicals is less usual. There is a possibility that degassing and dewatering of the sediment after coring could have led to these elements migrating up the core (M. Harper, pers. comm., 2003). The likelihood of such a process is difficult

to determine, but it would be a remarkable coincidence if the elements migrated up the core to the exact depth where changes are recorded in the diatom record.

The levels of silica recorded by geochemical analysis may not be accurate representations of the actual amounts available in the water column at the time of deposition. Instead, the measured levels may reflect the uptake by planktonic diatoms (M. Harper, pers. comm., 2003), resulting in higher Si levels once these diatoms are deposited. Because of the inability to determine diatom concentrations within the section, the role of this process in the record is unknown. The mobility of the different elements after sedimentation can also have a considerable affect on the geochemical signature recorded (Felitsyn & Kirianov, 2002). The most mobile of the significant elements in tephra is Si, whereas P has low mobility because it is highly reactive, while Al, as the least mobile element will tend to become concentrated in the residual tephra material (Felitsyn & Kirianov, 2002). Both of these factors will confuse the elemental record gleaned from sediment geochemistry analysis. However, the diatom assemblage can produce an accurate representation of the relative levels of Si and P in the water column. This is because taxa have different requirements for these elements (Tilman *et al*, 1982; Kilham 1984; Kilham *et al*, 1986). With regard to Si, the data indicates that the amount of Si available declined from RgZ1 into RgZ2, before becoming limiting in RgZ3. This is because the dominant diatom in RgZ1, *A. ambigua* requires high concentrations of Si, whereas *C. stelligera*, dominant in RgZ3, is an excellent competitor for Si, so can survive in low Si waters (Kilham, 1971; Kilham *et al*, 1986). This is in agreement with the sediment geochemistry data pertaining to RgZ1 and RgZ2, but not with RgZ3. One possible explanation could be a possible increase in diatom concentration in RgZ3, which was evident in the slide analysis, but because of the ineffectiveness of the addition of lycopodium spores, cannot be quantified. This will increase the amount of silica deposited. In addition, the prospect of continued in-washing of tephra particles into the lake from the catchment could play a role in the increase of the Si in RgZ3. However, if this did affect the Si budget, there would have been significant numbers of tephra particles included in the analysed samples, but none were identified in the slides. Additionally, Si could be supplied to the lake in the form of cations from the tephra and washed into the lake.

The phosphorus record confirms the pattern of diatom succession recorded by Si. The highest levels of P occur in RgZ1, progressively decrease through RgZ2, to level

out in RgZ3. *A. ambigua* requires high levels of P (Kilham *et al*, 1986), so the decline of P into RgZ2 likely produced conditions which restricted the ability of *A. ambigua* to survive, so the population dropped. When P fell to its lowest level at the transition from RgZ2 to RgZ3, conditions became such that *A. ambigua* was not able to compete effectively for the low levels of P available, so a significant population of *A. ambigua* could not be maintained. On the other hand, *C. stelligera* is a good competitor for phosphorus, so can survive when P becomes limiting (Kilham *et al*, 1986). Additionally, the effect of chemicals not analysed cannot be discounted. Examples of such elements are vanadium and germanium, which both affect the availability of silica to diatoms (M. Harper, pers. comm., 2003).

7.4.1.1 Shifts in diatom assemblage

Two significant events are recorded within the Rangitoto tephra section. Both of these events are present within the three data sets analysed, indicating that these are "real" changes representing events within the lake environment.

None tephra impact

The earliest change in this section is not tephra related. Based on sedimentation rates, it occurs approximately 60 years before the major event recorded at 29.25 cm. One possible cause of the initial event could be the development of early Maori settlements within the Lake Pupuke catchment (M. Harper, pers. comm., 2003). Evidence of Maori occupations has previously been discovered underneath the Rangitoto tephra in the Auckland region (Davidson, 1978; Nichol, 1992; Lowe *et al*, 2000), though, not at the Lake Pupuke site. Early Maori settlers cleared forested areas, specifically on hills, to free up land for food crops (Anderson, 1991). This would affect the lake environment in several ways. The removal of trees would decrease shelter provided to the lake, increasing windiness on the lake, therefore raising wind-induced currents, which would have increased turbulence and turbidity within the water column, and therefore increase the mixing depth and decrease the depth of the photic zone. In addition, burning was the common method of removing vegetation, which would, in combination with soil disturbance, have caused a short-term increase in nutrient supply to the lake. The dominant diatom taxa leading up to this initial event, *A. ambigua*, requires high Si and high P to survive, turbulence to remain afloat, and can survive in low light conditions (Kilham *et al*, 1986). The principal effects from

deforestation would be to improve growth conditions for this taxon, both by increasing nutrient availability and turbulence. However, *A. ambigua* declines significantly into RgZ2. Therefore, either deforestation produced an additional impact not listed above, which resulted in a reduction in the lakes nutrient budget as recorded in the section, or that deforestation caused by Maori settlement was not the mechanism behind the initial change in conditions within Lake Pupuke recorded at 37.25 cm, or approximately 1460 AD.

Delayed response to tephra input

The most significant event recorded in either Lake Pupuke or Pukaki Crater cores is recorded 1.75 cm above the Rangitoto tephra, at a depth of 29.25 cm. The lake records a dramatic shift towards oligotrophic conditions at this level, represented by a shift in diatom dominance to *C. stelligera*. There are three primary questions relating to this event that need answering:

1. Does the influx of the tephra cause the changes recorded up core, or is some mechanism unrelated to tephra input responsible?
2. Is this change driven by trophic status changes or is it simply an opportunistic take over by *C. stelligera* which happens to be oligotrophic? And,
3. If the tephra is responsible, why is there an offset recorded between the depth where the tephra is preserved and the change in diatom composition?

The default position must be that the influx of tephra had no impact on the diatom assemblage, and that the changes are a product of some unrelated process. Such a mechanism would have to affect the diatom assemblage very quickly, while simultaneously causing the environmental indicators and geochemical signature of the sediments to shift. Because Lake Pupuke is a deep lake within a closed basin, there is no inflow from outside the tuff ring. This is important because this controls the availability of nutrients supplied to the lake, in that the ability for any large-scale fluctuations in the supply of additional nutrients into the lake is limited. Therefore, environmental changes can be transmitted only through shifts within the tuff ring, or via the atmosphere (dust, sunlight, etc). The most likely mechanism would be regional climate change. A climatic shift is likely to have multiple affects on the lake ecosystem, resulting in changes in such variables as turbidity, turbulence, nutrient input, lake level, photic depth and salinity. The onset of the change recorded within the Rangitoto tephra section is very swift; less than 10 years based on the thickness of

the transition zone. This implies that the climate change must have been significant, but there is no supporting evidence for a change of this magnitude.

Biological interactions producing the change in diatom assemblage is also possible. The most likely of these would be selective predation or disease of the *A. ambigua* taxon. However, this does not explain the dramatic rise of *C. stelligera* in RgZ3 because while both these taxa are planktonic, they have different environmental requirements, so the possible loss of *A. ambigua* through such mechanisms is unlikely to result in an increase in *C. stelligera*.

The change recorded at the transition into RgZ3 represents a significant loss in the amount of dissolved nutrients in the lake waters, most notably P and N. If this produced the change in diatom assemblage, then this should be recorded in the sediment geochemistry data. The signature of P is one of significantly lower levels in RgZ3 than in RgZ1. However, the principal loss of P occurs in RgZ2, and the levels present at 29.25 cm have been attained at 34.25 cm, below the tephra bed and before the shift in trophic status is recorded. Similarly, the record of Fe, another key nutrient, records the same response across the section. Therefore, while the pattern of response of P and Fe is consistent with nutrient status controlling the change recorded at 29.25 cm, the timing is not. However, neither does it agree with the shift at 29.25 cm being an opportunistic take over by *C. stelligera*, as this taxon does not become dominant at 34.25 cm, when the low nutrient levels are achieved.

A more useful representation of the trophic status of the lake is recorded by the diatom taxa themselves. *A. ambigua*, a planktonic taxon, requires high concentrations of P and Si, whereas *C. stelligera*, also a planktonic taxa, is an excellent competitor for both elements, so can survive in lower concentrations (Kilham *et al*, 1986). This suggests that the amount of P and Si in the lake water dropped suddenly at 29.25 cm. Additionally, *S. ulna*, a benthic taxon, is a poor competitor for Si, but a good competitor for P (Kilham, 1984). This indicates that the availability of Si had a role in the changes recorded in both benthic and planktonic habitats, because taxa from both habitats were affected by the changing nutrient conditions. Therefore, from both the sediment geochemistry and the diatom data, it can be concluded that in RgZ1, there was a high level of Si and P available in the lake waters. In RgZ2, this began to change, with P dropping, especially in planktonic waters. It did not become limiting, however, as taxa that are poor competitors for P were able to remain prominent. Si continued to be non-limiting into RgZ2. At 29.75 cm, P and Si became limiting in

both benthic and planktonic habitats. This resulted in the only available oligotrophic, low Si requiring taxa, *C. stelligera*, to become dominant. This conclusion is reinforced by the fact that *Achnanthes minutissima*, one of the rare species that is only recorded above 29.25 cm, is an indicator of low nutrient conditions (Hall & Smol, 1992; Kelly and Whitton, 1995). Based on this evidence, it is clear that trophic status did drive the change recorded at 29.25 cm.

The probable role of tephra in this section was to seal off the underlying sediments, thereby cutting the supply of P to the lake. The physical affects of increased turbidity and decreased turbulence would have contributed to the loss of *A. ambigua*, though these effects seem secondary compared with the drop in nutrient status. While the lake was becoming less eutrophic towards 29.25 cm, the dramatic shift at this depth could not have been a product of diatom succession, and not based on any change in environmental conditions. Additionally, as *C. stelligera* is a planktonic diatom; benthic taxa would not be affected if the shift was caused by a change other than in environmental conditions within the lake. Therefore, it can be concluded that the tephra input was the probable cause of the event recorded at 29.25 cm.

This section records two major changes in both the environmental conditions and the diatom assemblage, although, the first was not produced by the tephra. The duration of the tephra-induced impact cannot be determined because pre-tephra conditions do not return before the top of the section. Therefore, all that can be stated is that this event effected the lake environment for at least 70 years. However, the magnitude of the event indicates that a semi-permanent shift in lake conditions was likely.

Comparison with previous studies

Decreased nutrient availability was the causal mechanism at only one site previously investigated, Lake Massoko, Tanzania (Barker *et al*, 2000). At Lake Massako, two individual tephra layers approximately 10 cm apart are recorded. The record across these tephras indicates that reduction in recycling of phosphorus from underlying sediments was the factor controlling the diatom assemblage. The deposition of the first, thin (1-2 cm) tephra, was not sufficient in sealing the underlying sediments, but did slow the rate of release, thereby P dropped. The influx of the second, thicker tephra (12 cm), however, was sufficient to seal the sediments. This caused the loss of the high-P requiring *Aulacoseira* spp., being replaced by *Synedra* spp., which are

good competitors for P (Barker *et al*, 2000). This record is most readily comparable to the Rangitoto tephra section, where again; two events are recorded. However, the presence of *Synedra* spp. as the dominant taxa after the tephra at the Tanzanian site indicates that silica did not decrease across the tephra as was recorded in the Rangitoto section.

A core extracted from Lake Tilo, Ethiopia (Telford, 1998; Telford & Lamb, 1999) records a shift from an *Aulacoseira* spp. dominated assemblage to a *Cyclotella stelligera* dominated lake across two tephra layers. Additionally, a lag time of 50 years is recorded between one of the tephra beds and the assemblage change. This record is very similar to that recorded across the Rangitoto tephra. While the response is the same, the controlling mechanism is not. In Lake Tilo, climate change produced changes in groundwater supply which resulted in salinity variations within the lake, which are believed to be controlling force on the diatom assemblage (Telford & Lamb, 1999). The authors conclude that the tephra had a minimal, if any impact on the diatom assemblage, and the offset recorded was purely coincidental. This illustrates the need for as many parameters and data sources to be utilised in the use of diatoms in recreating past environmental perturbations.

7.4.2 Tahua tephra

The Tahua tephra, at 10 mm, is the thinnest tephra preserved in the Lake Pupuke core (Fig. 7.6). *Cyclotella stelligera* is the dominant taxon within the section, followed by *Fragilaria pinnata*, and *Aulacoseira ambigua* respectively. No changes are recorded across the tephra but *A. ambigua* disappears from the lake 1.75 cm above the tephra bed. *A. ambigua* is the only diatom species to disappear at this level, and no other species are affected, indicating that the mechanism which led to the loss of *A. ambigua* acted specific to this taxon.

The diatom assemblage is also characterised by the increase in *C. stelligera* from the base of the section to the top. This increase is gradual, and significantly, shows no response across the tephra or to the disappearance of *A. ambigua*. This suggests that *C. stelligera* was responding to a long-term change in the conditions within the lake, instead of a direct response to the tephra input.

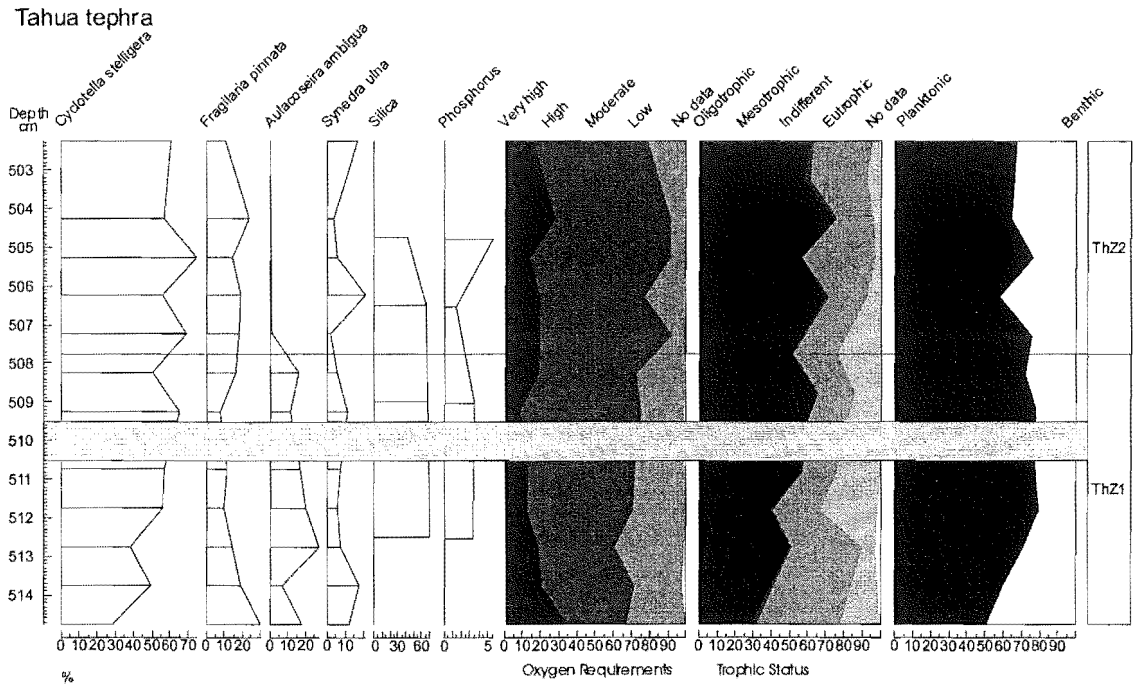


Figure 7.6: Selected results from Tahua tephra section

The majority of the autecological data displays no systematic changes through the section, with trophic status demonstrating the highest degree of conformity with the species data. This records the loss of eutrophic conditions 1.75 cm above the top of the tephra, at the depth where *A. ambigua* is lost, which indicates that the lake was principally oligotrophic, but did not become exclusively oligotrophic until after 507.75 cm.

Sediment geochemistry analysis was conducted on four samples selected across the central zone of the section (512.5 cm – 504.75 cm), principally focusing on the depth where *A. ambigua* disappears from the assemblage. The two most important elements associated with diatoms, silica and phosphorus, show little change across the tephra, but both record changes at 507.75 cm, where *A. ambigua* disappears (Fig 7.6).

The significant outcome from the geochemical analysis is that the changes in the concentrations of the various elements do not coincide with the tephra bed, and instead are recorded either simultaneous with, or very near to, the depth where *A. ambigua* is lost. The Si curve indicates that there was less Si available above this level. This is in agreement with the diatom flora record, as *A. ambigua* requires high concentrations of Si in lake waters, whereas *C. stelligera* is a good competitor for Si, so can survive in low concentration environments (Kilham *et al*, 1984). Therefore, the loss of Si above 507.75 cm would have severely restricted the survival of *A. ambigua*, while *C. stelligera* remained unaffected. Similarly, *A. ambigua* requires

high concentrations of P, which also decreases across this zone. However, the decline in P is very short-term, with it increasing to levels higher than during pre-tephra conditions in the next sample. This indicates that the concentration of Si is the dominant control on the diatom assemblage across the tephra.

A likely sequence of events within Lake Pupuke at the time of the Tahua tephra resulting in the loss of *A. ambigua* would be as follows:

1. The recycling of P from underlying sediments is blocked, producing a shift towards oligotrophic conditions. This affects the population of *A. ambigua*, which requires high levels of P.
2. Silica concentration subsequently declines. This does not affect *C. stelligera* because it does not have high requirements for Si.
3. A small level of P recycling recommences. Ordinarily, this may have allowed *A. ambigua* to recover, but the amount of Si available in the water has declined to levels below where *A. ambigua* can survive, so *C. stelligera* remains dominant.

The exact duration of trophic effects from the Tahua tephra is unknown. Tephra input could have produced two outcomes: the lake returned to pre-tephra conditions at some stage above the end of the section, or the lake was affected semi-permanently, and pre-tephra conditions were never recovered. A semi-permanent shift in the diatom assemblage could be produced by the tephra causing lake conditions to pass a threshold state, where the relatively small tephra input produced a major event. However, all that can be stated with certainty is that the impact continued for at least 105 years.

7.4.3 P36(T3) tephra

Tephra T3 is the only section, apart from T6 and T4, which records *Synedra ulna* v *spathulifera*. However, this taxon does not show any relationship with *Synedra ulna*, as recorded previously. *S. ulna* is present in very low numbers, and instead the diatom assemblage appears to record a response to changing nutrient conditions. Tephra T3 is 5 mm thick andesitic tephra recorded at 5481.5 cm from the Pukaki core (Fig. 7.7). The tephra is believed to be a Taranaki andesitic tephra, with a tentative correlation with the Poto tephra from Taranaki Volcano possible based on stratigraphic position relative to the Kawakawa tephra (Sandiford *et al*, 2001).

T3 is dominated by *Cyclotella stelligera* and *S. ulna* v *spathulifera*. A significant change is recorded 1 cm above the top of the tephra, which shows a sudden increase in *C. stelligera*, and a corresponding drop in *S. ulna* v *spathulifera*. The combined abundance explained by these two taxa remains consistent at 96% across the change, which would indicate a simple replacement relationship, however, as these two taxa inhabit different habitats (*C. stelligera* (planktonic) and *S. ulna* v *spathulifera* (benthic)), this is not plausible.

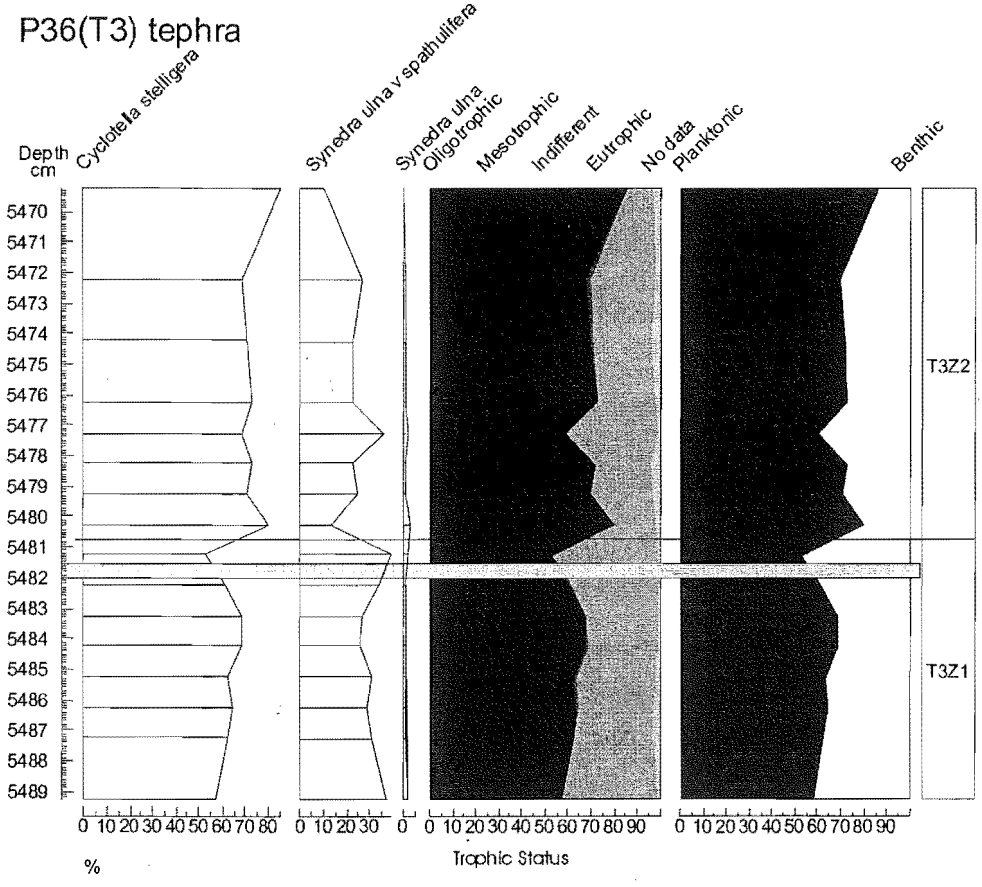


Figure 7.7: Selected results from T3 tephra section

Trophic status and oxygen saturation indicate a change in environmental conditions at the depth recorded by the shift in diatom assemblage (Fig. 7.7). This event did not affect pH, salinity or the availability of nitrogen within the lake waters. Oxygen saturation records a shift towards higher levels at this depth, while trophic status records a shift towards oligotrophic conditions and low levels of dissolved nutrients. Based on the data collected from this section, it is impossible to determine which of these environmental parameters was controlling, however, as trophic status has been the principal variable influenced by tephra input in many of the other sections analysed, it is probable that this is the case across the T3 tephra.

7.4.4 Mechanism of delayed response

Based on what is known about the changes recorded across these three tephras outlined above, there are three possible explanations as to the cause of this offset:

1. There was a delayed reaction by the diatom assemblage to the changing conditions caused by influx of the tephra,
2. There was a delayed release of nutrients from the tephra, or
3. The tephra is not in its correct stratigraphic position.

7.4.4.1 Delayed reaction to changing conditions

This possibility relies on diatom taxa being slow to react to changing environmental conditions, and that perhaps they only responded after the impact of the tephra reached some threshold values associated with trophic state. This is unlikely because diatoms are known to respond almost instantaneously to environmental changes because individual taxa have such specific optima and tolerances for many environmental variables (e.g. Vinebrooke, 1996). Additionally, the influx of the tephra, especially ones as thick as the Rangitoto tephra, would alter some aspects of the lake environment instantly upon deposition, particularly benthic habitats, but no change is recorded. Planktonic taxa dominate the assemblage across the Rangitoto, Tahua and T3 tephra, and settling tephra can have physical effects on these taxa, predominantly associated with increasing turbidity and lowering turbulence. These would affect the planktonic diatoms instantly because their habitat is exposed to the tephra as soon as it lands on the surface of the lake. However, no such change is recorded. Therefore, because there is an offset between tephra and response, a delayed reaction to changing conditions is unlikely.

7.4.4.2 Delayed release of nutrients

The dissolution process will begin as soon as tephra lands on the surface of a lake, when the elements that constitute the chemical structure begin to react with water and become released into the water column. The level of dissolution of individual elements will depend on their solubility in water, and the amount present in the tephra. Silica, with its high solubility and very high composition in tephra, will be the dominant element released. As silica is also the most biologically active component of tephra, especially to diatoms, the release of Si into the lake environment may

produce an instantaneous response. However, none is recorded. Therefore, the delayed release of nutrients is unlikely.

7.4.4.3 Settling of tephra through the lake floor

Because the specific gravity of tephra particles is high (1-2 $g.cc^{-1}$), and the sediment that accumulates at the sediment-water interface is soft and unconsolidated (<1 $g.cc^{-1}$), the angular tephra particles may sink through the unconsolidated material until they reach a depth where the strength of the sediment is such that it can sustain the weight of the tephra particles (Edmondson, 1984; Beierle & Bond, 2002). The prospect of the tephra layer sinking to below its true stratigraphic position has significant consequences when investigating the response of diatoms to tephra input. While the tephra may sink, diatoms will remain in the correct stratigraphic position because of their low specific gravity, and therefore any changes produced will be recorded at this level because the influx of tephra will produce an almost instantaneous response from both the diatom assemblage and the chemical makeup of the lake (Vinebrooke, 1996). This will be preserved in the sediment record as an apparent time lag between the tephra input and the response of the diatom assemblage. In this research, offsets range from 0.75 cm to 1.75 cm, representing 15 to 40 years.

The phenomenon of tephra settling through sediments has been previously described, although not frequently (e.g. Welch *et al*, 1982; Edmondson & Litt, 1984; Anderson *et al*, 1985; White & Osborn, 1992; Beierle & Bond, 2002). The occurrence of this process has not previously been identified using diatom assemblage data. In these other studies, the settling of tephra has been physically observed in historical eruptions (e.g. either Welch *et al*, 1982; Edmondson & Litt, 1984; Anderson *et al*, 1985), or inferred from irregularities in dates combined with sedimentological evidence (e.g. White & Osborn, 1992; Beierle & Bond, 2002). Several lakes surrounding Mt St Helens display tephra from the 1980 eruption underlying unconsolidated sediment laid down before the eruption. In one of these lakes, Williams Lake in eastern Washington, the tephra formed a 3-4 cm layer on the loose sediment surface, before sinking up to 83 cm through the underlying sediment. However, most of the material sank much less (cm – mm scale) (Anderson *et al*, 1985). In another lake, a thinner layer, several millimetres thick, behaved in the same manner, sinking a short distance through the sediment (Edmondson & Litt, 1984). In

older records, larger offsets have been recorded. In a section exposed in Copper Lake, Alberta, the White River tephra has been inferred to have sank the equivalent of 7800 years. The Mazama tephra, from the same site, records a 3000 years offset. The mechanics controlling this event have not been investigated, so the exact progression cannot be stated with certainty. The tephra can sink into the underlying sediments either as angular chunks of consolidated tephra (e.g. Anderson *et al*, 1985), or as a kind of fluid flow (e.g. White & Osborn, 1992). Additionally, experiments carried out monitoring tephra sedimentation in settling tubes demonstrates that tephra particles can sink several centimetres into underlying sediment, until a denser layer of sediment is encountered (Edmondson, 1984). At the Lake Pupuke and Pukaki Craters sites, fluid flow and the sinking of individual tephra particles are the probable processes controlling the sinking of tephra.

These findings are of paramount importance as the Auckland Maar Lakes are the focus of paleoenvironmental work which use tephra as the primary dating tool. This will be discussed in section 7.7.

7.5 *No response or unknown mechanism*

The majority of tephra deposited into the two sites produced responses in the diatom assemblages, but two tephras, T5 and T2, both from the Pukaki Crater site, appear to illicit no response.

7.5.1 P40(T5) tephra

The andesitic T5 tephra is the thinnest to be analysed in this research, at 2 mm (Fig. 7.8). T5 has not been geochemically linked to other andesitic deposits, but is believed to be sourced from Taranaki Volcano (Sandiford *et al*, 2001). This section has the least diversity of any analysed, with 18 taxa identified. The diatom assemblage is dominated by *Cyclotella stelligera*, which account for an average of 95% of the count, with *Synedra ulna* being the only other taxon that is present consistently. The tephra was probably too thin to have any physical effects, and not chemically distinct enough to alter nutrient levels within the lake

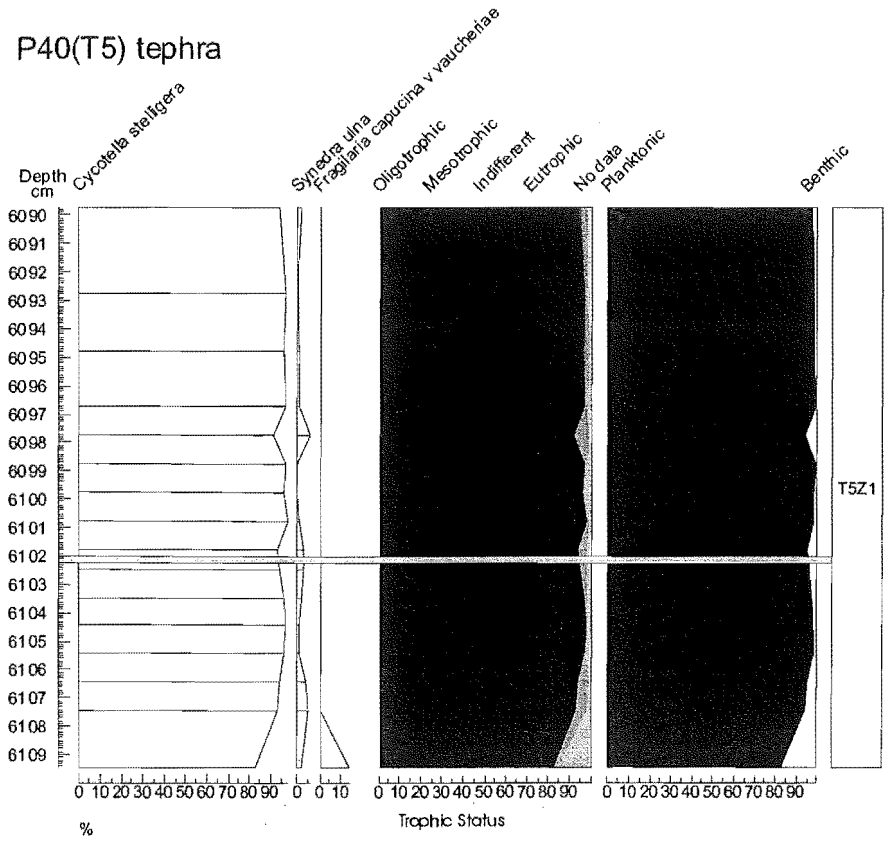


Figure 7.8: Selected results from T5 tephra section

7.5.2 P36(T2) tephra

The T2 tephra is the thickest tephra sampled from either site, at 20 cm. This tephra is basaltic in composition and has not been correlated to any source volcano, or to other tephra deposits preserved in the Auckland region. However, an approximate age for the tephra, of 21600 yrs BP, can be calculated by the use of known tephras and sedimentation rates (Sandiford *et al*, 2001).

As has been recorded in all the sections analysed from the Pukaki Core, *Cyclotella stelligera* is the dominant taxa, followed by *Synedra ulna* (Fig. 7.9). The diatom assemblage is divided up into 3 diatom zones based on the relative abundance of these two taxa. The transition from T2Z1 into T2Z2 occurs at 5470.75 cm, which is immediately below the tephra bed. The autecological indicators record no change across the tephra. The lake remains fresh water, with a pH of slightly above 7.0, and low in organically bound nitrogen. Oxygen saturation and trophic status are the only two environmental variables that record any changes within the section. The transition into T2Z2 records a shift towards higher oxygen levels and lower nutrient

status, while in T2Z3 the lake returned to conditions similar to those recorded in T2Z1.

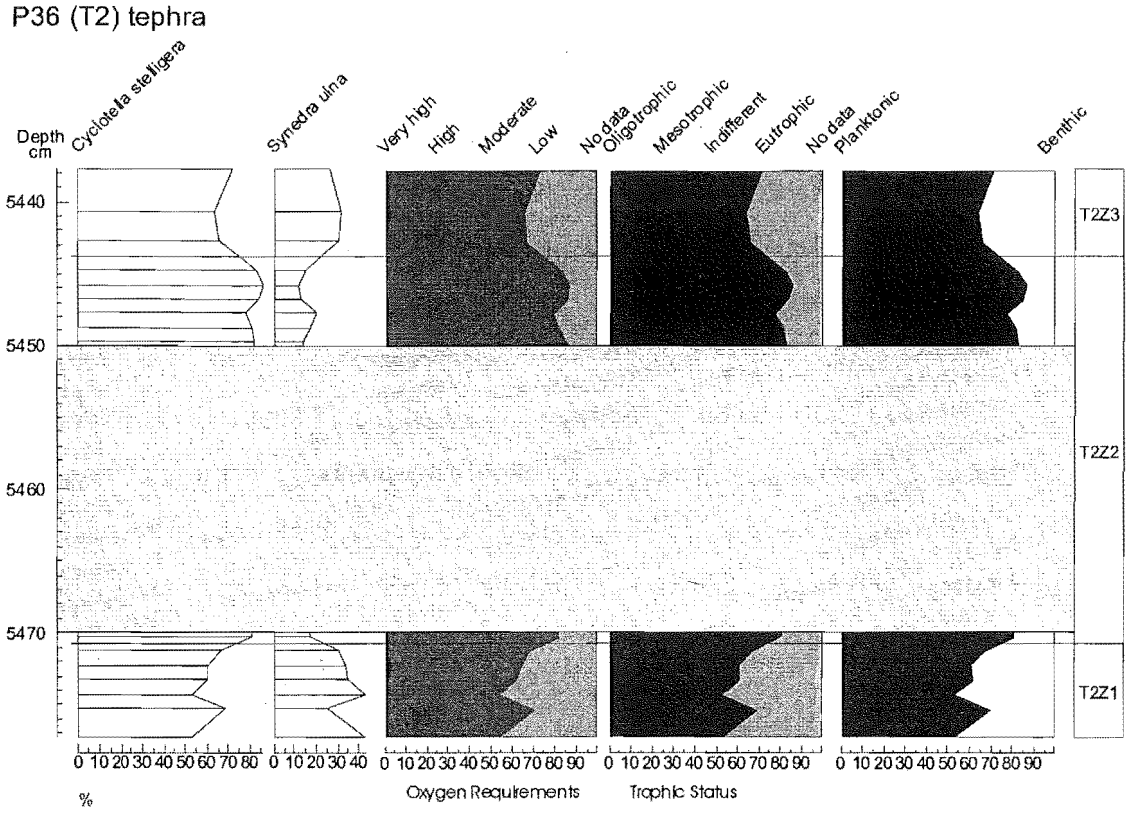


Figure 7.9: Selected results from T2 tephra section

7.5.3 Mechanisms of non-response

One of the project hypotheses was that thickness of tephra would influence any response of diatoms to tephra input. These two sections appear to prove one extreme of this hypothesis correct, and the other incorrect: that very thick and very thin tephra will not affect the diatom assemblage. However, conditions within the lake before tephra input may have had more control over this than the thickness of the tephra. In four of the seven other sections, increases in *Cyclotella stelligera* are recorded across the tephra, while none record decreases in this taxon. In both these cases, *C. stelligera* already comprises most of the assemblage; therefore, tephra input could not result in an increase in *C. stelligera.*

This is especially true for T5, being such a thin tephra. However, this does not adequately explain the non-response across T2, which as the thickest tephra recorded in this research, would have expected that have produced a response. The record across T2 is complicated by the fact that a response is recorded across the tephra, however, the onset of this change begins below the base of the tephra bed. This

indicates that it pre-dates the influx of the tephra, so therefore, as no additional shifts coincide with the tephra bed, the input of T2 tephra had no effect on the diatom assemblage or the lake environment. However, such a record could indicate a response to tephra input if the tephra bed can be shown to have moved up the core resulting in an offset in the opposite direction than recorded in other sections, or sunk down a considerable amount from above. There is no mechanism presently known that can move a tephra bed several centimetres up a core, especially one 20 cm in thickness, however, as described in section 7.4.4.3, tephra sinking through lake sediment is possible. Because of the thickness and density of T2, the likelihood of this occurring is high. The distance the tephra may have sunk cannot be determined. A significant change is recorded 6.25 cm above the top of the tephra, at 5443.75 cm, showing a drop in *C. stelligera* and rise in *S. ulna*. The tephra is unlikely to have initially been deposited at this depth because no such response to tephra input has been recorded in any other section. It is more probable that the tephra has sunk from above this depth, beyond the limits of the sampling.

The chemical properties of the lake environment prior to tephra input could also have played a role in the diatom response. The input of the basaltic T2 tephra into a basaltic maar lake is unlikely to release any chemicals not already present within the lake. The other two basaltic tephras analysed in this research record changes in the diatom assemblage, with the Rangitoto tephra recording the most significant response of any section. However, the lake environment into which the Rangitoto tephra was deposited was unstable, having undergone a major event just 60 years earlier. If the Pukaki Crater was stable when the tephra was deposited, it is possible that it had no chemical affect on the environment. However, if the tephra has sunk a considerable depth, then the true response of the tephra is not recorded within this section, and until additional sampling above this depth is undertaken, it will not be known.

7.6 *Characteristics of the tephra impact*

Assuming that the argument about delayed responses to tephra impacts is accepted, the specific changes associated with the tephras are as follows:

7.6.1 Unaffected environmental variables

pH remained unchanged across all of the tephra beds except one – T6. Therefore, it can be concluded that the input of tephra had no little effect on the pH of either of the lakes, which remained slightly alkaline. Similarly, tephra input did not affect the salinity of the lakes, remaining fresh water lakes throughout the duration of the core length. Likewise, the availability of organically-bound nitrogen compounds was unaffected by tephra input.

7.6.2 Impact recorded

The majority of the sections recorded a change across the tephra bed, however, the mechanisms that produced these changes is variable.

7.6.2.1 Physical

Two tephras show physical characteristics of the tephra as being responsible for the changes recorded in the data. Across the Rotoma tephra the settling tephra smothered and buried benthic habitats for a period of approximately 125 years, when pre-tephra conditions returned. This was because the lake at the time was dominated by benthic taxa, which are particularly prone to these processes. The Taupo tephra records physical affects of the tephra on planktonic diatoms, while the submergence of waterweeds affects selected benthic taxa. Significantly, these two sections record the highest abundance of benthic taxa from in this study. This suggests that physical properties of the tephra will only be important when benthic taxa comprise a high proportion of the diatom assemblage.

Additionally, indirect physical effects of burying pre-tephra sediments, thereby shutting down the recycling of P from these sediments into the lake has a considerable impact on several sections, most notably, across the Rangitoto tephra.

7.6.2.2 Chemical

The apparent dominant effect was the blocking of recycling of P from pre-tephra sediments. This results in a shift towards oligotrophic conditions across nearly all the tephra beds. This controls the response of the diatoms, and invariably results in an increase in *Cyclotella stelligera*, at the expense of all other planktonic taxa, and

increases in benthic habitats of rare oligotrophic taxa at the expense of common eutrophic taxa.

The level of Si within the water column also decreases across the majority of the tephras. This indicates that either the level of dissolution of silica from the tephra was low, which is unlikely, or that plankton blooms after tephra input soaked up the remaining Si, or most likely, the reduction in P overrides this response. In this case the loss of Si recorded by the diatom assemblage after tephra input is associated with the change in assemblage produced by the lower levels of P, and not by changes in Si.

7.6.3 Influence of tephra composition and thickness on type and duration of impact

One of the hypotheses of this research was that the composition and thickness of the tephra would influence the response recorded in the diatom assemblage. The composition of tephra is thought to influence any changes in lake environments because of differences in the chemical makeup and densities of the different types of tephra. Likewise, tephra thickness will influence lakes by the controlling the amount of tephra in the water column and the impacts on benthic environments.

7.6.3.1 Type of response

Within the sections analysed, there appears to be no definitive pattern in the response produced by the influx of tephras of different composition or thickness (Table 7.2). The most significant example of this is from the Kawakawa and T6 tephras, which both display the same response from tephra events that are different in composition and thickness. This is unusual because while the mechanism controlling this response is not understood, it is believed to be responsive to changes in water chemistry (see section 7.3). This suggests that the specific characteristics of the tephra are not significant; instead, general properties of tephra may be important.

The two sections across which physical responses are recorded are both thick rhyolitic tephras. However, the exact responses recorded are different; the Rotoma tephra suppresses benthic taxa, while the Taupo tephra enhances the population of *S. ulna*, a benthic taxon. This suggests that while thick tephras are required for the physical properties of tephra to become important, the exact response produced is not entirely dependant on the thickness. The rate of accumulation may be critical in

determining the response of benthic assemblages to input of thick tephra. Rapid deposition of tephra may result in some taxa becoming buried when they would survive a gradual rainout.

Table 7.1: Tephra response characteristics

Tephra composition	Tephra I.D.	Tephra thickness (mm)	Duration of response (years)	Response type
Rhyolitic	Kawakawa (T4)	7	50	chemical
	Rotoma	50	125	physical
	Tahua	10	>105	chemical
	Taupo	65	75	physical
Andesitic	T5	2	0	none
	T3	5	>600	chemical
Basaltic	Rangitoto	25	>70	chemical
	T6	<5	50	chemical
	T2	200	unknown	unknown

Three sections record reductions in phosphorus across the tephra. These three tephras, Rangitoto, Tahua and T3 represent the 3 tephra compositions: basaltic, rhyolitic and andesitic respectively. This indicates that tephra composition does not influence this mechanism. Additionally, thickness does not appear significant, with these tephra ranging from 5-25 mm, though there may be a critical maximum thickness. T5, at 2 mm, appears to be the case in point. In contrast, the non-response to T2 is puzzling, but may well be a function of undersampling, with the actual responses occurring up the core from the top sample point.

Additionally, the thickness or composition of the tephra does not appear to be a dominant control on the sinking of tephra through underlying lake sediments. Of the five tephra where this mechanism is recorded, Tahua, Rangitoto, Taupo, T3 and T2, two are rhyolitic, two basaltic and one andesitic, and thicknesses vary from 5 mm to 200 mm. Likely processes responsible for the sinking of tephra are discussed in section 7.7.

7.6.3.2 Duration of impact

The duration of the tephra effects vary between tephras and between sites. The time-scales produced are not concise as they are created using average sedimentation rates using tephrachronological markers. They do provide, however, a general picture of the duration of effects within the different sections. The data indicates that neither the thickness nor composition of the tephra influences the duration of the event on the diatom assemblage.

The durations vary from no impact (T5), to at least 600 years (T3). These extremes are both produced by thin andesitic tephras, which indicates that chemical makeup or thickness of andesitic tephra does not control the duration of the response in the diatom assemblage. Similarly, basaltic and rhyolitic compositions of the tephra appear to have no influence on the duration of any response (Table 7.2).

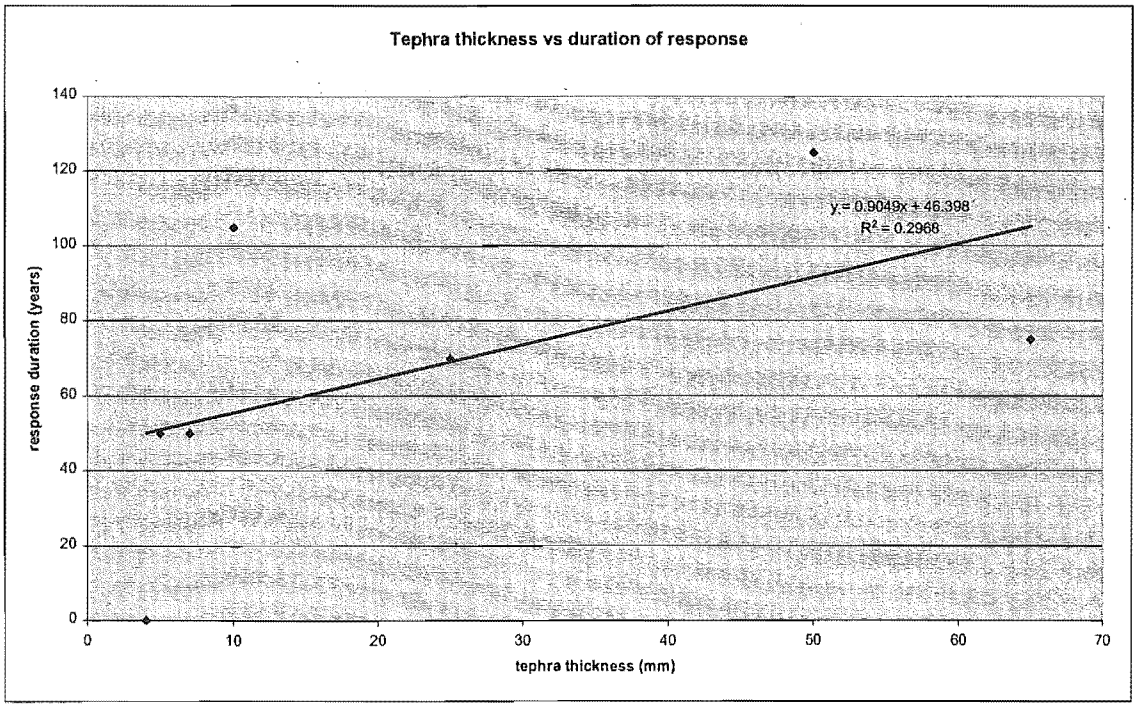


Figure 7.10: Tephra thickness vs. response duration

The relationship between tephra thickness and duration of impact is shown in Figure 7.10. T2 and T3 tephras are excluded from this graph, as T2 is unknown and T3 appears as an outlier. The graph shows a weak positive relationship, with an R^2 value of approximately 0.30. This suggests that the duration of response will increase with increased thickness, though this relationship will not always be solid, and any inference beyond the lower end of the thickness-duration relationship should be made with caution.

7.7 *Implications for paleoenvironmental studies*

The significant result from this study is the suggestion that tephra can sink through sediment on the bottom of lakes. This raises the question of what are the likely characteristics of tephras that result in them sinking through the sediment. What separates tephras that sink through the underlying sediment from those which do not? There are two factors that likely determine which tephras are affected by this process:

1. Physical properties of the tephra particles, and
2. Sedimentary conditions on the lake bottom.

Important properties include the rate of tephra influx, density of the tephra and size of the grains, along with the sedimentation rate within the lake.

The rate of tephra influx will determine the rate of deposition of tephra on the lake bottom, as well as influence the behaviour of the tephra particles in the water column. This is significant because if a large amount of tephra is deposited on the lake surface, there will be a high level of interaction between the tephra particles in the water column. This may lead to the formation of conglomerations of tephra, which will have a mass considerably higher than that of single tephra particles. Therefore, these tephra blebs are more likely to settle through the sediment on the lake bottom than individual tephra particles. The rate of arrival of tephra will depend on the size of the eruption and its proximity to the site.

The density of the tephra particles will influence the duration of particle suspension, and the likelihood of the tephra sinking through sediment. Tephra particles have an average density of 1-2 $g.cc^{-1}$, while lake sediment is generally less than 1 $g.cc^{-1}$ (Beierle & Bond, 2002). This will create a mass imbalance on the lake bottom, which may result in the denser tephra particles sinking through the sediment. The densest tephra is produced by basaltic eruptions, and there is a progression through to rhyolitic tephras which are the lightest.

The size of the grains will also influence the likelihood of tephra sinkage. Smaller particles require less displacement of obstructing sediment, so will be able to sink through the underlying sediment easier. Additionally, smaller tephra particles may fit into pore spaces created by sediment deposition, resulting in easier movement through the sediment. Basaltic tephra has the smallest grain sizes.

The sedimentary conditions on the lake bottom will also dictate the ease at which tephra can sink into the sediment, with the consolidation of the sediment being the

primary influence. If sediment is unconsolidated and soupy, it will have very low inherent strength with which to support the denser tephra. This will result in the tephra sinking through easily. Sedimentation rate is a good indicator of sedimentary conditions on the bottom of the lake, with a higher rate producing more consolidated sediment. In Lake Pupuke, the average sedimentation rate is 0.06 cm/yr^{-1}, while in Pukaki Crater it is 0.02 cm/yr^{-1}, which means that tephra sinking is more likely to occur in Lake Pupuke. This is supported by this research which demonstrates 3 out of 4 tephras from the Lake Pupuke core having likely sunk, whereas only 2 out of 5 from the Pukaki Crater core. However, the plethora of laminations recorded across tephras in Auckland maar lakes (Pepper, 2002) suggests that, at least in these lakes, grain by grain dissemination is the most likely sinking mechanism.

Physical properties of tephra can be easily calculated from samples extracted from cores, and while sedimentation rates will indicate what the conditions are like at the sediment/water interface, the exact conditions is more difficult to determine. This is especially true in lakes that have been infilled, such as Pukaki Crater, which requires the identification of tephras of known age. In present-day lakes, samples can be extracted from the present sediment/water interface, which will provide a definitive correlation with past events.

7.7.1 Implications

The majority of paleoenvironmental reconstructions are based on records extracted from lakes – both present, like Lake Pupuke, and past, as in Pukaki Crater. Maar lakes, especially, have been recognized as key sites for recording paleoclimate information, and have therefore been studied extensively, predominantly in Europe (i.e. EUROMAAR project (Zolitschka & Negendank, 1993), the European Lake Drilling Project (Zolitschka & Negendank, 1999), and the EUROMAAR Project (Zolitschka, 1992)). Accurate dating of the extracted record is required before paleoenvironmental work can begin, with chronologies usually provided by dating known tephras. In specific relation to the wider study program that this research was associated with, high-resolution maar lake records are used to provide verification for the annual deposition of laminae within maar lakes (Pepper, 2002). This study indicates that precise corroboration of such records is not possible unless the tephras can be shown to have not sunk through the underlying sediment.

The maar lake investigated in the related study was Onepoto Maar Crater, approximately 3 km southwest from Lake Pupuke. Three sections of the core were focused on, the early Holocene (9.5 – 10.2 ka), the deglaciation (13.9 – 17.6 ka), and the Last Glacial Maximum (LGM) (22.6 – 23.5 ka) (Pepper, 2002). Annual laminations can be said to occur if the age ranges produced by the laminae count and the mechanism of annual bloom or overturn of the lake are equal to the age range calculated from the tephras. The analysis, by Pepper (2002), indicated that in some parts of the core, the laminations appear to be annual, whereas in others, there are too few laminae to be recording annual deposition (Table 7.3). Even in the least convincing case, the laminae are out by a factor of two or less. The differential sinking of tephra through underlying sediment could add enough additional uncertainty to the age estimates to make the assignment of annual laminations more difficult, but it could also make the unmatching laminae counts possibly annual. This has potential application across all climate records.

Table 7.2: Tephra layers, dates and laminae counts from Onepoto Crater core (Source: Pepper, 2002).

Sample Number	Depth (m)	Tephras	Age (conventional radiocarbon years)^	Age (calibrated age range, years BP)*	Max& Min Age Ranges	Laminae Counts
2	36.25	Rotoma	8530±10BP	9545-9490	760-605	348
	36.36	Opepe	9050±40BP	10250-10150		
4	37.00	Waiohau	11850±60BP	14350-13450	2800-400	857
	37.18	Rotorua	13080±50BP	16250-14750		
5	37.47	Rerewhakaaitu	14700±110BP	18250-16950	3500-700	918
7	38.37	Kawakawa	22590±230BP	23100-22100	1610-150	809
	38.63	Okaia	23500±100BP	23710-23300		

Chapter eight: Conclusion

8.1 *Summary of Results*

The aim of this project was to determine the response of diatoms to the influx of tephra into their freshwater lacustrine environment. This was achieved by using three types of analysis: diatom assemblage data, autecological data and sediment geochemistry data. The analyses show that:

- Diatoms do respond to the influx of tephra into their environment. For only one out of the nine sections analysed can it be unequivocally stated that the tephra had no impact, with the majority of the sections recording increases in the taxon, *Cyclotella stelligera*, across the tephra bed. However, the response recorded by the diatom flora is not consistent across the different tephra beds.
- The most common environmental response is the reduction in phosphorus availability after tephra input due to the sealing off of underlying sediments by the consolidated tephra layer, blocking the recycling of P from pre-tephra deposits. This causes oligotrophic conditions to dominate, and generally results in *Cyclotella stelligera* becoming the dominant taxon. This is recorded for three of the nine tephras, the Rangitoto, Tahua and T3 tephras.
- Two sections, Rotoma and Taupo tephras, suggest physical interactions between the tephra particles and diatom habitats as the controlling mechanism for changes in the diatom assemblage. I postulate a smothering of epiphytic habitats by the Rotoma and Taupo tephras, and additionally by decreasing turbulence in planktonic waters because of increased levels of tephra particles within the water column across the Taupo tephra.
- In two sections, T4 and T6, tephra alters the relationship between *Synedra ulna* and a teratological variety of *Synedra ulna* v *spathulifera*, producing a very short-term replacement of S. *ulna v. spathulifera* by *S. ulna*. This is most likely the result of a change in chemical characteristics in benthic habitats following tephra input, however the exact cause is not known.

- Only two sections record tephra as having no impact on the diatom assemblage. However, only for T5, the thinnest tephra analysed, can this be stated unequivocally. The non-response recorded across T2, the thickest tephra analysed, is believed to be because the tephra has sunken through the sediment.
- The most significant outcome from this research is the recognition that tephra can sink through sediment on the bottom of a lake. This is recorded as an offset between the depth at which the tephra is currently preserved and the depth where the effects of the tephra input are recorded by the diatom assemblages. Five of the nine records such an offset (Taupo, Tahua, Rangitoto, T3 and T2 tephras). These offsets measure between 0.75 cm to 1.75 cm, or 15 to 40 years. These offsets recorded across the thickest tephra (T2, at 200 mm), has not been determined because it is likely that it is beyond the chosen sampling range
- Only weak positive relationships are evident between thickness of tephra and duration of response, while none is recorded between thickness of tephra and the type of response. Similarly, no relationship is apparent between chemical composition and type or duration of response.
- The possibility that some tephras may not be preserved in their original stratigraphic position has significant implications for paleoenvironmental investigations which utilise tephras as a dating and correlating tool. If tephras are shown to have sunk through underlying sediment, stratigraphic ages and correlations calculation from analysis of the tephras will be incorrect. This may undermine the tephrachronological framework for region correlations.
- However, diatom analysis of the kind performed in this research may assist in the identification of such events.

8.2 *Future work*

There are several areas where further research is recommended, both to verify the results produced in this study and to test the conclusions drawn. These include:

- Analyses using independent methods, such as chironomids, of the sediment record across Rangitoto, Tahua, Taupo, T3 and T2 tephras to verify the displacement of the tephra beds from their original stratigraphic positions.
- Diatom concentration analysis across the tephras sampled in this research. This will compliment the species analysis conducted across the tephras, and is required because of the ineffectiveness of the addition of lycopodium spores.
- Investigation across additional tephras within the Pukaki Crater core and at other sites to determine whether similar diatom responses are recorded.
- Additional analysis on the teratological form of *Synedra ulna* v *spathulifera*, to determine the processes leading to the formation of this aberrant taxon, and its relationship to *Synedra ulna*, and to the lake conditions in Pukaki Crater at the time.
- The instigation of a study where diatom analysis on lake sediments is completed before tephras have been identification within the lake, with the presence of tephra layers being predicted based on the patterns observed in the diatom analysis.

8.3 *Concluding statement*

This project provides vital information on the response of diatoms to tephra input and the behaviour of tephra in lakes, and raises significant questions about the use of tephras in paleoenvironmental investigations. My hope is that these findings will encourage additional research in this field.

References Cited

Abella, S.E.B. 1988: The effect of the Mt. Mazama ashfall on the planktonic diatom community of Lake Washington. *Limnology Oceanography 33*: 1376-1385

Allen, S.P. 1992: Volcanic hazards in the Auckland volcanic field. Unpublished M.Sc thesis, University of Auckland. 157 p.

Allen, S.R., Smith, I.E.M. 1994: Eruption styles and volcanic hazards in the Auckland Volcanic Field, New Zealand. Geoscience Reports of Shizuoka University. Pp. 5-14

Allen, S.R., Bryner, V.F., Smith, I.E.M., Balance, P.F. 1996: Facies analysis of pyroclastic deposits within basaltic tuff-rings of the Auckland volcanic field, New Zealand. *New Zealand Journal of Geology and Geophysics 39*: 309-327

Alloway, B., Neall, V.E., Vucetich, C.G. 1995: Late Quaternary (post 28 000 year B.P.) tephrostratigraphy of northeast and central Taranaki, New Zealand. *Journal of the Royal Society of New Zealand 25*: 385-458

Anderson, A.J. 1991: The chronology of colonization in New Zealand. *Antiquity 65*: 767-795

Anderson, R.Y., Nuhfer, E.B., Dean, W.E. 1985: Sinking of volcanic ash in uncompacted sediment in Williams Lake, Washington. *Science 225*: 505-508

Anderson, N.J. 2000: Diatoms, temperature and climate change. *Journal of Ecology 75*: 926-946

Barker, M.A. 1967: The limnology of Lake Pupuke – with special reference to the zooplankton. Unpublished M.Sc thesis, University of Auckland. 146 p.

Barker, P., Telford, R., Merdaci, O., Williamson, D., Taieb, M., Vincens, A., Gibert, E. 2000: The sensitivity of a Tanzanian crater lake to catastrophic tephra input and four millennia of climate change. *The Holocene 10*: 303-310

Baross, J.A., Dahm, C.N., Ward, A.K., Lilley, M.D., Sedell, J.R. 1982: Initial microbial response in lakes to the Mt St Helens eruptions. *Nature 296*: 49-52

Barsdate, R.J., Dugdale, R.C. 1972: Effects of volcanic ashfalls on chemical and sediment characteristics of two Alaskan lakes. *Journal of Fisheries Research Board of Canada 29*: 229-236

Battarbee, R. W. 1986: Diatom analysis. *In*: Berglund, B.E. *ed.* Handbook of Holocene paleoecology and paleohydrology. John Wiley & Sons, Chichester. Pp. 527-570

Battarbee, R.W. 2000: Paleolimnological approaches to climate change, with special regard the biological record. *Quaternary Science Reviews 19*: 107-124

Battarbee, R.W., Charles, D.F., Dixit, S., Renberg, I. 1999: Diartoms as indicators of surface water acidity. *In*: Stoermer, E.F., Smol, J.P., *eds.* The diatoms: applications for the environmental and earth sciences. Cambridge University Press, Cambridge. Pp. 85-127

Battarbee, R.W., Jones, V.J., Flower, R.J., Cameron, N.G., Bennion, H., Carvalho, L., Juggins, S. 2001: Diatoms. *In*: Smol, J.P., Birks, H.J.B., Last, W.M., *eds.* Tracking environmental change using lake sediments. Volume 3: terrestrial, algal, and siliceous indicators. Kluwer Academic Publishers, Dordrecht. Pp. 155-202.

Beirele, B., Bond, J. 2002: Density-induced settling of tephra through organic lake sediments. *Journal of Paleolimnology 28*: 433-440

Bennion, H., Juggins, S., Anderson, N.A. 1996: Predicting epilimnetic phosphorus concentrations using and improved diatom-based transfer function and its application to lake eutrophication management. *Environmental Science & Technology 30*: 2004-2007

Berglund B., Persson, T. 1999: Lycopodium spore tablets (Batch 938934) information sheet. 2 p.

Birks, H.J.B., Lotter, A.F. 1994: The impact of the Laacher See Volcano (11 000 yr B.P.) on terrestrial vegetation and diatoms. *Journal of Paleolimnology 11*: 323-322

Brant, L.A., Bahls, L.L. 1995: Paleoenvironmental impacts of volcanic eruptions upon diatom community. *In*: Kociolek, P., Sullivan, M.J., *eds*, A Century of Diatom Research in North America: a tribute to the distinguished careers of Charles W. Reimer & Ruth Patrick. Balogh Scientific Books, Illinois. Pp 151-157

Büchel, G. 1993: Maars of Westeifel (Germany). *In*: Negendank J.F.W., Zolitschka, B., *eds*. Paleolimnology of European Maar Lakes. *Lecture Notes in Earth Sciences 49*: 1-14

Campbell, J.B. 1986: New Occurrences and distribution of Kawakawa Tephra in South Island, New Zealand. *New Zealand Journal of Geology and Geophysics 29*: 425-435

Carter, L., Nelson, C.S., Neil, H.L., Froggatt, P.C. 1995: Correlation, dispersal, and preservation of the Kawakawa Tephra and other late Quaternary tephra layers in the Southwest Pacific Ocean. *New Zealand Journal of Geology and Geophysics 38*: 29-46

Cassidy, J., Locke, C.A., Miller, C.A., Rout, D.J. 1999: The Auckland volcanic field, New Zealand; geophysical evidence for its eruption history. *Geological Society Special Publications 161*: 1-10

Cassie, V. 1989: A contribution to the study of New Zealand Diatoms. Bibliotheca Diatomologica: Band 17. J. Cramer, Berlin. 265 p.

Christie, S.E., Smol, J.P. 1993: Diatom assemblages as indicators of lake trophic status is southern Ontario lakes. *Journal of Phycology 29*: 575-586

Cleve, P.T. 1894: Synopsis of naviculoid diatoms. Kgl. Sven. Vet. Akad. Handl 26: 1-194

Cleve, P.T. 1895: Synopsis of naviculoid diatoms. Kgl. Sven. Vet. Akad. Handl 27: 1-219

Cleve-Euler, A. 1922: Om diatomacevegetationen och dess förandringar I Sabysjön, Uppland, samt några dämda sjöar I Salatrakten. *Sver. Geol. Undres. C309*: 1-76

Coomber, C.L. 1998: A Holocene evolution of a marine breached maar lake: Pukaki Crater, New Zealand. Unpublished MSc thesis, University of Auckland. 117 p.

Creer, K.M., Thouveny, N 1996: Preface. *Quaternary Science Reviews 15*: 99-100

Cronin, S.J., Wallace, V.E., Neall, V.E. 1996: Sourcing and identifying andesitic tephras using major oxide titanomagnietite and hornblende chemistry, Egmont volcano and Tongariro Volcanic Centre, New Zealand. *Bulletin of Volcanology 58*: 33-40

Cronin, S.J., Hedley, M.J., Neall, V.E., Smith, R.G. 1998: Agronomic impact of tephra fallout from the 1995 and 1996 Ruapehu Volcanic eruptions, New Zealand. *Environmental Geology 34*: 21-30

Darley, W.M. 1977: Biological composition. *In*: Werner, D., *ed.* The biology of diatoms.Botanical Monographs 13. Blackwell Scientific Publications, Oxford. Pp. 198-223

Davidson, J.M. 1978: The prehistory of Motutapu Island, New Zealand: five centuries of Polynesian occupation in a changing landscape. *Journal of the Polynesian Society 87*: 327-337

Davies-Colley, R.J. 1988: Mixing depths in New Zealand lakes. *New Zealand Journal of Marine and Freshwater Research 22*: 517-527

Eden, D.N., Froggatt, P.C. 1988: Identification and significance of distal Aokautere Ash in three loess cores from Eastern South Island, New Zealand. *In*: Eden, D.N., Furkert, R.J., *eds.* Loess, its distribution, geology and soils. Rotterdam, A.A. Balkema. Pp. 47-58

Edmondson, W.T. 1984: Volcanic ash in lakes. *Northwestern Environmental Journal 1*: 139-150

Edmonson, W.T., Litt, A.H. 1984: Mt. St.Helens ash in lakes in the lower Grand Coulee, Washington State. *Proceedings - International Association of Theoretical and Applied Limnology 22*: 510-512

Feldt, L.E., Stoermer, E.F., Schelske, C.L. 1973: Occurrence of morphologically abnormal Synedra populations in Lake Superior phytoplankton. Proceedings of the 16th Conference of Great Lakes Research 1973: 34-39

Felitsyn, S.B., Kirianov, V. Y. 2002: Mobility of phosphorus during weathering of volcanic ashes. *Lithology and Mineral Resources 37*: 275-278

Foged, N. 1979: Diatoms in New Zealand, the North Island. Bibliotheca Phycologica: Band 47. J. Cramer, Berlin. 224 p.

Foth, H.D. 1990: Fundamentals of Soil Science. John Wiley & Sons, Chichester. 360p.

Fritz, S.C., Kingston, J.C., Engstrom, D.R. 1993: Quantitative trophic reconstruction from sedimentary diatom assemblages: a cautionary tale. *Freshwater Biology 30*: 1-23

Fritz, S.C., Cumming, B.F., Gasse, F., Laird, K. 1999: Diatoms as indicators of hydrologic and climatic change in saline lakes. *In*: Stoermer, E.F., Smol, J.P., *eds.* The diatoms: applications for the environmental and earth sciences. Cambridge University Press, Cambridge. Pp. 41-72

Froggatt, P.C., Lowe, D.J. 1990: A review of late Quaternary silicic and other tephra formations from New Zealand: their stratigraphy, nomenclature, distribution, volume, and age. *New Zealand Journal of Geology and Geophysics 33*: 89-109

Gasse, F. 1987: Diatoms for reconstructing paleoenvironments and paleohydrology in tropical semi-arid zones. Examples of some lakes from Niger since 12,000 BP. *Hydrobiologia 154*: 127-163

Green, J.D. 1975: Light penetration. *In*: Jolly, V.H., Brown, M.A., *eds.* New Zealand Lakes. Auckland University Press, Auckland. Pp. 84-89

Green, J.D., Viner, A.B., Lowe, D.J. 1987: The effects of climate on lake mixing patterns and temperatures. *In*: Viner, A.B. *ed.* Inland waters of New Zealand. DSIR Bulletin 241. Department of Scientific and Industrial Research, Wellington. Pp. 65-95

Grönlund, T., Kauppila, T. 2002: Holocene history of Lake Soldatskoje (Kola Peninsula, Russia) inferred from sedimentary diatom assemblages. *Boreas 31*: 273-284

Grover, J.P. 1988: Dynamics of competition in a variable environment: experiments with two diatoms species. *Ecology 69*: 408-417

Haberyan, K.A. 1998: The effect of volcanic ash influx on the diatom community of Lake Tanganyika, East Africa. *Transactions, Missouri Academy of Science 32*: 102-105

Hägg, J.H. 2002: Aspects of the paleoenvironmental record from Onepoto maar crater, Auckland. Unpublished M.Sc thesis, University of Auckland. 145 p.

Hall, R.I., Smol, J.P. 1992: A weight-averaged regression and calibration model for inferring total phosphorus concentration from diatoms in British Columbia (Canada) lakes. *Feshwater Biology 27*: 417-434

Hall, R.I., Smol, J.P. 1999: Diatoms as indicators of lake eutrophication. *In*: Stoermer, E.F., Smol, J.P., *eds*. The diatoms: applications for the environmental and earth sciences. Cambridge University Press, Cambridge. Pp. 128-166

Hardardóttir, J., Geirsdóttir, Á., Thordarson, T., 2001: Tephra layers in a sediment core from Lake Hestvatn, southern Iceland: implications for evaluating sedimentation processes and environmental impacts on a lacustrine system caused by tephra fall deposits in the surrounding watershed. *In*: White, J.D.L., Riggs, N.R., *eds*. Volcaniclastic Sedimentation in lacustrine Environments. *Special Publication of the International Association of Sedimentologists 30*: 225-247

Harper, M.A., Howorth, R., McLeod, M. 1986: Late Holocene diatoms in Lake Poukawa: effects of airfall tephra and changes in depth. *New Zealand Journal of Marine and Freshwater Research 20*: 107-118

Hay, R.F., Mutch, A.R., Watters, W.A. 1970: Geology of the Chatham Islands. *New Zealand Geological Survey bulletin 83*

Heiken, G., Wohletz, K.H. 1985: Volcanic Ash. University of California Press, Berkeley, California. 245 pp.

Heming R.F., Barnett, P.R. 1986: The petrology and petrochemistry of the Auckland Volcanic Field. *Royal Society of New Zealand Bulletin 23*: 64-75

Hickman, M., Reasoner, M.A. 1994: Diatom response to late Quaternary vegetation and climate change, and to deposition of two tephras in an alpine and subalpine lake in Yoho National Park, British Columbia. *Journal of Paleolomnology 11*: 173-188

Hickman, M., Reasoner, M.A. 1998: Late Quaternary diatom response to vegetation and climate change in a subalpine lake in Banff national park, Alberta. *Journal of Paleolomnology 20*: 253-265

Hill, C.F. 1975: Impounded lakes of the Waikato River. *In*: Jolly, V.H., Brown, M.A., *eds.* New Zealand lakes. Auckland University Press, Auckland. Pp. 140-149

Hoare, R.A., Spigel, R.H. 1987: Water balances, mechanics and thermal properties. *In*: Vant, W.N., *ed.* Lake Managers Handbook: A guide to undertaking and understanding investigations into lake ecosystems, so as to assess management options for lakes. Water and Soil Miscellaneous Publications 103. Ministry of Works and Development Centre, Wellington. Pp. 41-58

Hogg, A.G., McCraw, J.D. 1983: Late Quaternary tephras of Coromandel Peninsula, North Island, New Zealand: a mixed peralkaline and calcalkaline tephra sequence. *New Zealand Journal of Geology and Geophysics 26*: 163-187

Holmes, C.C. 1994: Aspects of the limnology of Lake Pupuke, with special reference to the phytoplankton. Unpublished MSc thesis, University of Auckland. 153 p.

Houghton, B.F., Wilson, C.J.N., Smith, I.E.M. 1999: Shallow-seated controls on styles of explosive basaltic volcanism: a case study from New Zealand. *Journal of Volcanology and Geothermal Research 91*: 97-120

Husdedt, F. 1937: Systematische und ökologische Untersuchungen über den Diaomeen-Floa von Java, Bali, Sumatra. *Archeology hydrobiology15*

Husdedt, F. 1939: Systematische und ökologische Untersuchungen über den Diaomeen-Floa von Java, Bali, Sumatra. *Archeology hydrobiology 16*

Husdedt, F. 1956: Kieselalgen (Diatomeen). Kosmos-Verlag Franckh, Stuttgart

Hutchinson, G.E. 1957: A treatise on limnology volume 1: geography, physics and chemistry. John Wiley & Sons, New York. 368 p.

Irwin, J. 1975: Morphology and classification. *In*: Jolly, V.H., Brown, M.A., *eds.* New Zealand Lakes. Auckland University Press, Auckland. Pp. 25-56

Kelly, M.G., Whitton, B.A. 1995: The Trophic Diatom Index: a new index for monitoring eutrophication in rivers. *Journal of Applied Phycology 7*: 433-444.

Kermode, L.O. 1992: Geology of the Auckland urban area. Scale 1:50000. *Institute of Geological & Nuclear Sciences geological map 2.* Lower Hutt, Institute of Geological and Nuclear Sciences. 63 p. and 1 sheet

Kilham, P. 1971: A hypothesis concerning silica and the freshwater planktonic diatoms. *Limnology Oceanography 16*: 10-18

Kilham, S.S. 1984: Silicon and phosphorus growth kinetics and competitive interactions between Stephanodiscus minutes and Synedra sp. *Proceedings - International Association of Theoretical and Applied Limnology 22*: 435-439

Kilham, P., Kilham, S.S. 1990: Endless summer; internal loading processes dominate nutrient cycling in tropical lakes. *Freshwater Biology 23*: 379-389

Kilham, P., Kilham, S.S., Hecky, R.E. 1986: Hypothesized resource relationships among African planktonic diatoms. *Limnology Oceanography 31*: 1169-1181

Kohn, B.P. 1979: Identification and significance of a late Pleistocene tephra in Canterbury District, South Island, New Zealand. *Quaternary Research 11*: 78-92

Kolkwitz, R., Marsson, M. 1908: Ökologie der pflanzlichen Saprobien. *Ber. Dt. Bot. Ges 26a*: 505-519

Korsman, T., Birks, H.J.B. 1996: Diatom-based water chemistry reconstructions from northern Sweden: a comparison of reconstruction techniques. *Journal of Paleolimnology 15*: 65-77

Krammer, K. and Lange-Bertalot, H. 1986. Bacillariophyceae. 1. Teil: Naviculaceae. *In*: Ettl, H., Gerloff, J., Heynig, H. and Mollenhauer, D. *eds*. Süsswasser flora von Mitteleuropa, Band 2/1. Gustav Fischer Verlag: Stuttgart, New York. 876 p.

Krammer, K. and Lange-Bertalot, H. 1988. Bacillariophyceae. 2. Teil: Bacillariaceae, Epithemiaceae, Surirellaceae. *In*: Ettl, H., Gerloff, J., Heynig, H. and Mollenhauer, D., *eds*. Süsswasserflora von Mitteleuropa, Band 2/2. VEB Gustav Fischer Verlag: Jena. 596 p.

Krammer, K. and Lange-Bertalot, H. 1991a. Bacillariophyceae. 3. Teil: Centrales, Fragilariaceae, Eunotiaceae. *In*: Ettl, H., Gerloff, J., Heynig, H. and Mollenhauer, D., *eds*. Süsswasserflora von Mitteleuropa, Band 2/3. Gustav Fischer Verlag: Stuttgart, Jena. 576 p.

Krammer, K. and Lange-Bertalot, H. 1991b. Bacillariophyceae. 4. Teil: Achnanthaceae, Kritische Ergänzungen zu Navicula (Lineolatae) und Gomphonema, Gesamtliteraturverzeichnis Teil 1-4. *In*: Ettl, H., Gärtner, G., Gerloff, J., Heynig, H. and Mollenhauer, D., *eds*. Süsswasserflora von Mitteleuropa, Band 2/4. Gustav Fischer Verlag: Stuttgart, Jena. 437 p.

Kurenkov, I.I. 1966: The influence of volcanic ashfall on biological processes in a lake. *Limnology Oceanography 11*: 426-429

Larsen, G. 1981: Tephrachronolgy by microprobe glass analysis. *In* Self, S., Sparks, S.J. *eds*. Tephra Studies. D. Reidel, Dordrecht. Pp 95-102.

Lotter, A.F., Birks, H.J.B. 1993: The impact of the laacher See Tephra on terrestrial and aquatic ecosystems in the Black Forest, southern Germany. *Journal of Quaternary Science 8*: 263-276

Lotter, A.F., Birks, H.J.B., Hofmann, W., Marchetto, A. 1998: Modern diatom, cladocera, chironomid, and chrsophyte cyst assemblages as quantitative indicators for the reconstruction of past environmental conditions in the Alps. II. Nutrients. *Journal of Paleolminology 19*: 443-463

Lowe, D.J. 1988a: Late Quaternary volcanism in New Zealand; towards an integrated record using distal airfall tephras in lakes and bogs. Journal *of Quaternary Science 3*: 111-120

Lowe, D.J. 1988b: Stratigraphy, age, composition and correlation of late Quaternary tephras interbedded with organic sediments in Waikato lakes, North Island, New Zealand. *New Zealand Journal of Geology and Geophysics 31*: 125-165

Lowe, D.J., Newnham, R.M., McFadgen, B.G., Highham, T.F.G. 2000: Tephras and New Zealand Archaeology. *Journal of Archaeological Science 27*: 859-870

Lowe, R.L., 1974, Environmental requirements and pollution tolerance of freshwater diatoms: Cincinnati, Ohio, U.S. Environmental Protection Agency, National Environmental Research Center, Office of Research and Development, EPA-670/4-74-005. 334 p.

Maberly, S.C., Hurley, M.A., Butterwick, C., Corry, J.E., Heany, S.I., Irish, A.E., Jaworski, G.H.M., Lund, J.W.G., Reynolds, C.S., Roscoe, J.V. 1994: The rise and fall of *Asterionella formose* in the South Basin of the Windermere: analysis of a 45-year series of data. *Freshwater Biology 31*: 13-34

Mackereth, F.J.H. 1969: A short core sampler for subaqeous deposits. *Limnology Oceanography 14*: 145-151

Main, W.L., Barnes, P.M. 1989: Lake Pupuke 1:3500, Lake Series, N.Z. Oceanographic Institute, Department of Scientific Research, Wellington.

Mann, D.G., Droop, J.M. 1996: Biodiversity, biogeography and conservation of diatoms. *Hydrobiologia 336*: 19-32

McBirney, A.R. 1968: Compositional variations of the climactic eruption of Mount Mazama. *Oregon Department of Geology and Mineral Industries Bulletin 62*: 53-56

McFarland, B.H., Hill, B.H., Willingham, W. T. 1997: Abnormal Fragilaria spp. (Bacillariophyceae) in streams impacted by mine drainage. *Journal of Freshwater Ecology 12*: 141-149

McIntosh, P.D., Eden, D.N., Burgham, S.J., Froggatt, P.C. 1988: Volcanic glass and terrace chronology in the Gore region, Southland. *Geological Society of New Zealand newsletter 80*: 54-56

Menyailov, L.A., Nikitina, L.P., 1980: Chemistry and metal content of magmatic gases: the new Tolbachik volcanoes case (Kamchakta). *Bulletin of Volcanology 43*: 197-205

Mew, G., Hunt, J.L., Froggatt, P.C., Eden, D.N., Jackson, R.J. 1986: An occurrence of Kawakawa Tephra from the Grey River valley, South Island, New Zealand. *New Zealand Journal of Geology and Geophysics 29*: 315-322

Mildenhall, D.C. 1979: Exotic pollen rain on the Chatham Islands during the late Pleistocene. *New Zealand Journal of Geology and Geophysics 15*: 251-261

Nairn, I.A. 1991: Volcanic Hazards of Okataina Volcanic Centre. Volcanic Hazards Information Series No. 2. 29 p.

Negendank, J.F.W., Zolitschka, B. 1993a: Maars and maar lakes of the Westeifel Volcanic Field. *In*: Negendank J.F.W., Zolitschka, B., *eds*. Paleolimnology of European Maar Lakes. *Lecture Notes in Earth Sciences 49*: 61-80

Negendank, J.F.W., Zolitschka, B. 1993b: International Maar Deep Drilling Project (MDDP) – A challenge for earth sciences? *In*: Negendank J.F.W., Zolitschka, B. *eds*. Paleolimnology of European Maar Lakes. *Lecture Notes in Earth Sciences 49*: 505-510

Nelson, C.S., Froggatt, P.C., Gosson, G.J. 1986: Nature, chemistry and origin of Late Cenozoic megascopic tephras in Leg 90 cores from the Southwest Pacific. *In*: Kennett, J.P., von der Borch, C.C., Baker, P.A., Barton, C.E., Boersma, A., Caulet, J.P., Dudley, W.C., Gardner, J.V., Jenkins, D.G., Lohman, W.,H, Martini, E., Merrill, R.B., Morin, R.H., Nelson, C.S., Robert, C., Srinivasan, M.S., Stein, R., Takeuchi, A., *eds*. Initial reports of the Deep Sea Drilling Project leg 90. Pp. 1161-1173

Newnham, R.M., Lowe, D.J. 1991: Holocene vegetation and volcanic activity, Auckland Isthmus, New Zealand. *Journal of Quaternary Science 6*: 177-196

Newnham, R.M., Lowe, D.J., Alloway, B. 1999: Volcanic hazards in Auckland, New Zealand: a preliminary assessment of the threat posed by central North Island silicic volcanism based on the Quaternary tephrostratigraphic record. *London Geological Society Special Publication 161*: 27-45

Nichol, R. 1992: The eruption history of Rangitoto: reappraisal of a small New Zealand myth. *Journal of the Royal Society of New Zealand 22*: 159-180

Patrick, R., Reimer, C.W. 1966: The diatoms of the United States Volume 1. Academy of Natural Sciences of Philadelphia Monograph No. 13. Academy of Natural Sciences of Philadelphia, Philadelphia. 688 p.

Patrick, R. 1971: The effects of increasing light and temperature on the structure of diatom communities. *Limnology Oceanography 16*: 405-421

Patrick, R. 1977: Ecology of freshwater diatoms and diatom communities. *In*: Werner, D., *ed.* The biology of diatoms. Botanical Monographs 13. Blackwell Scientific Publications, Oxford. Pp. 284-332

Pepper, A.C. 2002: Late Quaternary climate records using laminated lake sediments from an Auckland maar carter, (Onepoto Maar), New Zealand. Unpublished M.Sc thesis. University of Canterbury, New Zealand. 171 p.

Pillans, B., Wright, I. 1992: Lake Quaternary tephostratigraphy from the southern Havre Trough, Bay of Plenty, northeast New Zealand. *New Zealand Journal of Geology and Geophysics 35*: 129-143

Pridmore, R.D. 1987: Phytoplankton response to changed nutrient concentrations. *In*: Vant, W.N., *ed.* Lake Managers Handbook: A guide to undertaking and understanding investigations into lake ecosystems, so as to assess management options for lakes. Water and Soil Miscellaneous Publications 103. Ministry of Works and Development Centre, Wellington. Pp. 183-194

Reiser, U. 2001: Pukaki 1-01: Initial luminescence dating and radiometric measurements. *In*: Dickinson, W.W., *ed.* Preliminary Scientific Data Report, Pukaki 1-01, Pukaki Maar Crater, Auckland, New Zealand. Victoria School of Earth Sciences Research Report 14. Pp. 13-16

Reid, T. 1979: Water resource report: Lake Pupuke. Auckland Regional Water Board Technical Publication No. 11. 20 p.

Reynolds, C.S. 1982: Phytoplankton periodicity: its motivation, mechanism and manipulation. 50th Annual Report, Biological Association, Ambleside, UK. Pp. 60-75

Reynolds, C.S. 1984: The ecology of freshwater phytoplankton. Cambridge University Press, Cambridge. 384 p.

Rhoades, D.A., Dowrick, D.J., Wilson, C.J.N. 2002: Volcanic Hazards in New Zealand: scaling and attenuation relations for tephra fall deposits from Taupo volcano. *Natural Hazards 26*: 147-174

Round, F.E., Crawford, R.M., Mann, D.G. 1990: The diatoms: biology and morphology of a genera. Cambridge University Press, Cambridge. Pp. 747

Rout, D.J., Cassidy, J., Locke, C.A., Smith, I.E.M. 1993: Geophysical evidence for temporal and structural relationships within the monogenetic basalt volcanoes of the Auckland Volcanic Field, northern New Zealand. *Journal of Volcanology and Geothermal Research 57*: 71-83

Sandiford, A., Alloway, B.V., Shane, P.A.R. 2001: A 28000-6600 cal yr record of local and distal volcanism preserved in a paleolake, Auckland, New Zealand. *New Zealand Journal of Geology and Geophysics 44*: 323-336

Sandiford, A., Horrocks, M., Newnham, R.M., Alloway, B. 2002: Environmental reconstruction of the Last Glacial Maximum (c. 25000-16500 years B.P.) at Mt Richmond, Auckland Isthmus, New Zealand. *Journal of the Royal Society of New Zealand 32*: 155-167

Saros, J.E., Fritz, S.C. 2002: Resource competition among saline-lake diatoms under varying N:P ratios, salinity, and brine type. *Freshwater Biology* 47: 87-95.

Schmid, A.-M., M., Borowitzka, M.A., Volcani, B.E. 1981: Morphogenesis and biochemistry of diatom cell walls. *In*: Kiermayer, O., *ed.* Cytomorphogenesis in Plants. *Cell Biology Monographs 8*: 63-97

Searle, E.J. 1964: City of volcanoes: a geology of Auckland, New Zealand. Longman Paul, Auckland. 112 p.

Searle, E.J. 1981: City of volcanoes: a geology of Auckland, New Zealand (2nd edition). Longman Paul, Auckland. 195 p.

Shane, P.A.R. 2000: Tephrachronology: a New Zealand case study. *Earth-Science Reviews 49*: 223-259

Shane, P.A.R., Hoverd, J. 2002: Distal record of multi-sourced tephra in Onepoto Basin, Auckland, New Zealand; implications for volcanic chronology, frequency and hazards. *Bulletin of Volcanology 64: 441-454*

Shane, P.A.R., Smith, I.E.M. 2000: Geochemical fingerprinting of basaltic tephra deposits in the Auckland Volcanic Field. *New Zealand Journal of Geology and Geophysics 43*: 569-577

Shulmeister, J., Dickinson, W.W. 2001: Introduction. *In*: Dickinson, W.W., *ed.* Preliminary Scientific Data Report, Pukaki 1-01, Pukaki Maar Crater, Auckland, New Zealand. Victoria School of Earth Sciences Research Report 14. Pp. 1-8

Skille, J.M., Falter, C.M., Kendra, W.R., Schuchard, K.M. 1983: The fate, distribution and limnological effects of volcanic tephra in the St. Joe and Coeur d'Alene River deltas of Lake Coeur d'Alene, Idaho. Forest, Wildlife and Range Experiment Station Contribution no. 253. 145 p.

Sonneman, J.A., Sincok, A., Fluin, J., Reid, M., Newall, P., Tibby, J., Gell., P. 1999: An illustrated guide to common stream diatom species from temperate Australia. Cooperative Research Centre for Freshwater Ecology, Thurgoona, Australia. 63 p.

Stoermer, E.F., Ladewski, T.B. 1976: Apparent optimual temperatures for the occurance of some common phytoplankton species in southern Michigan. Great Lakes Research Division Publication no. 18. 49 p.

Stoermer, E.F., Smol, J.P. 1999: Applications and uses of diatoms: prologue. *In*: Stoermer, E.F., Smol, J.P., *eds.* The diatoms: applications for the environmental and earth sciences. Cambridge University Press, Cambridge. Pp. 3-10

Telford, R.J. 1998: Diatom stratigraphies of Lakes Awassa and Tilo, Ethiopia: Holocene records of groundwater variability and climate change. Unpublished PhD Thesis, University of Wales. 312 p.

Telford, R.J., Lamb, H.F. 1999: Groundwater-mediated response to Holocene climatic change recorded by the diatom stratigraphy of an Ethiopian Crater Lake. *Quaternary Research 52*: 63-75

Tilman, D. 1977: Resource competition between planktonic algae: an experimental and theoretical approach. *Ecology 58*: 338-348

Tilman, D., Kilham, S.S., Kilham, P. 1982: Phytoplankton community ecology: the role of limiting nutrients. *Annual Review of Ecological Systems 13*: 349-372

Van Dam, H., Mertens, A., Sinkeldam, J. 1994: A coded checklist and ecological indicator values of freshwater diatoms from the Netherlands. *Netherlands Journal of Aquatic Ecology 28*: 117-133

Vant, W.N., Pridmore, R.D. 1990: Plant nutrients in Lake Pupuke – a report to B.T. Coffey and Associates Ltd. For North Shore District Council. Water Quality Centre Consultancy Report 8602. Department of Scientific and Industrial Research, Hamilton. 12 p.

Verdiun, J. 1952: The volume-based phytosynthetic rates of aquatic plants. *American Journal of Botany 39*: 157-159

Vinebrooke, R.D. 1996: Abiotic and biotic regulation of periphyton in recovering acidified lakes. *Journal of the North American Benthological Society 15*: 318-331

Walker, G.P.L. 1980: The Taupo pumice: product of the most powerful known (ultraplinian) eruption? *Journal of Geothermal Research 9*: 395-407

White, J.M., Osborn, G.D. 1992: Evidence for a Mazama-like tephra deposited ca. 10,000 BP at Copper Lake, Banff National Park, Alberta. *Canadian Journal of Earth Sciences 29*: 52-62

Wilson, C.J.N. 1993: Stratigraphy, chronology, styles and dynamics of late Quaternary eruptions from Taupo Volcano, New Zealand. *Philosophical Transactions of the Royal Society of London A 343*: 205-306

Wilson, C.J.N., Rogan, A.M., Smith, I.E.M., Northey, D.J., Nairn, I.A., Houghton, D.F. 1985: Caldera volcanoes of the Taupo Volcanic Zone, New Zealand. *Journal of Geophysical Research 89*: 8463-8484

Wilson, C.J.N., Houghton, B.F., McWilliams, M.O., Lamphere, M.A., Weaver, S.D., Briggs, R.M. 1995: Volcanic and structural evolution of the Taupo Volcanic Zone, New Zealand: a review. *Journal of Volcanology and Geothermal Research 68*: 1-28

Wood, I.A. 1991: Thermoluminescence dating of the Auckland and Keikeri basaltic fields. Unpublished M.Sc thesis, University of Auckland. 141 p.

Zolitschka, B. 1992: Climate change evidence and lacustrine varves from maar lakes, Germany. *Climate Dynamics 6*: 229-232

Zolitschka, B., Negendank, J.F.W. 1993: Lago Grande di Monticchio (Southern Italy): A high resolution sedimentary record of the last 70,000 years. *In:* Negendank J.F.W., Zolitschka, B., *eds.* Paleolimnology of European Maar Lakes, *Lecture Notes in Earth Sciences 49*: 277-288

Zolitschka, B., Negendank, J.F.W. 1999: High-resolution records from European Lakes. *Quaternary Science Reviews 18*: 885-88

Appendices

Appendix A: Diatom Counts

Table A.1: Diatom counts for Rotoma tephra section

Sample depth	592.75	589.75	585.75	583.75	581.75	579.75	578.75	577.75	572.25	571.25	570.25	568.25	566.25	564.25	562.25	558.25	554.25	550.25	546.25	SUM	%
Fragilaria pinnata	164	211	192	95	87	127	152	114	57	87	113	82	147	131	40	157	143	68	137	2304	39.724
Cyclotella stelligera	91	69	94	54	47	131	69	50	127	130	98	118	50	54	142	56	66	137	73	1656	28.552
Synedra ulna	37	36	34	33	18	62	32	20	67	31	35	66	17	32	104	25	25	66	44	784	13.517
Epithemia sorex	19	25	18	4	11	5	10	2	5	3	7	1	15	13	1	13	11	3	9	175	3.017
unidentified Fragilaria	11	12	19	0	0	3	3	2	3	6	9	0	0	8	0	23	12	0	0	111	1.914
Fragilaria construens + var	39	4	3	1	2	2	6	2	1	1	1	0	0	0	0	0	1	0	0	63	1.086
Cocconeis placentula + vars	3	0	2	1	5	2	2	2	10	6	5	3	3	6	1	2	3	6	5	67	1.155
Epithemia adnata	3	6	4	0	5	4	1	0	1	0	1	1	7	5	1	2	3	0	5	49	0.845
Achnanthes exigua	1	0	0	0	0	3	3	0	3	8	4	2	4	1	2	3	1	4	4	43	0.741
Navicula radiosa	1	1	0	1	0	3	2	0	2	4	3	3	2	2	1	0	1	1	2	29	0.500
Amphora coffaeformis	0	1	1	1	5	3	1	2	1	0	1	1	3	4	1	0	2	0	1	28	0.483
Nitzschia spp.	0	2	1	1	0	0	1	0	2	3	1	2	0	1	2	0	1	2	1	20	0.345
Achnanthes cleveli	0	1	1	1	0	3	0	0	0	0	2	2	1	1	3	2	0	3	1	21	0.362
unidentified Navicula	0	3	0	0	0	0	0	0	3	9	0	0	0	0	1	0	0	0	0	16	0.276
Mastogloia elliptica	0	1	2	0	2	0	0	0	0	0	0	0	4	3	0	2	0	0	1	15	0.259
Stauroneis phoenicenteron	0	1	0	1	0	1	1	0	2	2	1	0	2	2	0	0	2	0	0	15	0.259
Cymbella affinis	0	0	1	0	0	0	0	0	1	1	0	1	1	1	0	0	4	4	1	15	0.259
Achnanthes lanceolata v frequentissima	2	1	1	1	2	0	0	0	0	0	4	0	1	0	0	0	0	0	0	12	0.207
Gomphonema parvulum	0	0	0	0	0	0	0	1	0	4	4	2	0	0	0	0	0	0	0	11	0.190
Aulocoseira ambigua	0	1	0	2	0	2	0	0	0	0	0	2	2	0	0	0	0	2	0	11	0.190
Navicula gregaria	1	0	0	0	0	0	0	1	4	0	0	0	0	0	1	0	2	0	0	9	0.155
Cymbella cistula	0	1	0	0	0	1	0	0	1	0	1	0	0	0	0	2	1	0	0	7	0.121
Navicula viridula	4	0	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	7	0.121
Achnanthes cf. minutissima	2	1	0	0	0	1	0	0	0	1	2	0	0	0	0	0	0	0	0	7	0.121
Achnanthes subatomoides	1	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0.086
Eunotia spp.	1	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	1	0	0	5	0.086
Navicula bacillum	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0.052
Stephanodiscus cf. alpinus	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0.052
Navicula placentula	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	3	0.052
Navicula pupula	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	3	0.052
Pinnularia spp.	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0.052
Rhopalodia novae zealandiae	0	2	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	3	0.052
Achnanthes brevipes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	2	0.034
Diploneis cf smithii	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0.034
Pinnularia divergens	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2	0.034
Fragilaria zeilleri	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.017
Navicula carl	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.017
Navicula cuspidata	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0.017
Surirella splendida	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.017
Surirella spp	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.017
Lychopodium Spores	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	4	0.069
Chrysophycean cysts	0	0	0	0	0	30	15	2	8	0	4	3	10	5	0	0	7	1	3	88	1.517
Fragments of sponge spicules	14	14	22	4	14	13	2	2	0	1	0	11	30	30	0	11	11	2	13	194	3.345
DIATOM SUM	400	400	400	200	200	400	300	200	300	300	300	300	300	300	300	300	300	300	300	5800	100

Table A.2: Diatom counts for Taupo tephra section

Sample depth	194.75	192.75	191.75	190.75	189.75	187.75	180.75	179.75	178.75	177.75	176.75	174.75	172.75	170.75	167.75	SUM	%
Cyclotella stelligera	165	175	195	135	96	126	92	132	177	139	105	164	74	150	129	2054	34.233
Aulocoseira ambigua	67	64	47	119	147	166	167	105	74	39	187	79	245	161	82	1749	29.150
Fragilaria pinnata	63	40	52	49	81	41	65	73	42	63	52	53	30	43	67	814	13.567
Synedra ulna	56	5	31	21	16	20	10	44	64	107	5	19	18	12	75	503	8.383
Fragilaria construens + var	5	71	30	39	18	17	14	6	7	9	22	27	14	3	6	288	4.800
Nitzschia spp.	6	4	3	6	6	4	8	2	9	3	7	15	2	1	4	80	1.333
Acnanthes subatomoides	3	3	3	5	9	6	9	13	9	7	2	0	0	1	3	73	1.217
Cocconeis placentula + vars	4	5	5	7	4	3	5	3	2	2	2	9	1	3	6	61	1.017
Achnanthes cleveii	3	4	5	4	5	3	6	4	3	2	3	0	0	1	3	46	0.767
Navicula radiosa	2	1	3	4	3	5	0	0	6	4	7	1	2	1	2	41	0.683
Achnanthes exigua	3	0	0	0	2	0	2	5	2	6	2	3	4	0	6	35	0.583
Gomphonema parvulum	2	4	9	0	4	1	0	3	2	1	2	1	1	1	2	33	0.550
Unidentified Fragilaria 2	5	1	0	3	4	0	0	0	0	11	0	0	0	0	4	28	0.467
Epithemia sorex	1	0	0	0	1	1	3	5	1	0	0	5	0	2	4	23	0.383
Achnanthes cf. minutissima	1	4	1	1	0	0	0	3	1	0	4	3	0	0	0	18	0.300
Unidentified Fragilaria 1	0	0	3	0	0	2	0	0	0	0	0	9	0	0	3	17	0.283
Epithemia adnata	0	6	1	0	0	0	4	0	0	0	0	0	1	0	0	12	0.200
Navicula bacillum	3	2	0	0	0	0	1	0	0	2	0	2	0	0	2	12	0.200
Cymbella affinis	1	1	1	1	1	0	0	1	0	0	0	3	0	2	0	11	0.183
Navicula viridula	0	0	0	2	0	0	1	0	0	1	0	0	0	0	1	5	0.083
Rhopalodia novae zealandiae	0	0	1	0	0	0	1	0	1	0	0	1	0	0	0	4	0.067
Diploneis cf smithii	0	1	0	1	0	0	0	0	0	0	0	0	0	1	0	3	0.050
Navicula placentula	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0	3	0.050
Surirella spp	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	3	0.050
Fragilaria crotonensis	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	2	0.033
Navicula cari	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	2	0.033
Achnanthes brevipes	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0.017
Achnanthes lanceolata v frequentissima	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0.017
Aulacoseira cf. granulata ends	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.017
Fragilaria zeilleri	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0.017
Navicula cuspidata	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0.017
Stauroneis phoenicenteron	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0.017
Fragments of sponge spicules	9	8	6	3	3	3	10	0	0	4	0	2	7	18	1	74	1.233
DIATOM SUM	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	6000	100

Table A.3: Diatom counts for Tahua tephra section

Sample depth	514.75	513.75	512.75	511.75	510.75	509.25	508.25	507.25	506.25	505.25	504.25	502.25	SUM	%
Cyclotella stelligera	114	148	152	169	172	195	152	277	169	224	170	183	2125	54.487
Fragilaria pinnata	121	56	59	30	35	24	49	73	56	42	71	31	647	16.590
Aulacoseira ambigua	72	20	108	60	51	34	49	7	0	0	0	2	403	10.333
Synedra ulna	46	52	29	17	23	33	17	9	63	17	12	49	367	9.410
Achnanthes exigua	11	3	10	7	3	1	6	1	1	0	6	6	55	1.410
Cocconeis placentula + vars	1	1	5	5	3	3	5	7	1	8	3	4	46	1.179
Epithemia sorex	4	1	4	3	1	0	6	6	1	1	6	0	33	0.846
Nitzschia spp.	6	2	3	2	1	0	5	2	0	2	3	1	27	0.692
Achnanthes cleveii	5	1	4	1	0	2	1	3	0	1	5	3	26	0.667
Achnanthes cf. minutissima	0	0	2	1	3	1	1	1	2	1	2	10	24	0.615
Gomphonema parvulum	0	0	0	2	1	0	3	1	3	0	3	3	16	0.410
Cymbella affinis	2	0	0	0	0	1	0	2	2	0	4	2	13	0.333
Navicula radiosa	2	1	1	1	1	2	0	0	0	1	4	0	13	0.333
Achnanthes lanceolata v frequentissima	2	0	1	0	2	0	0	2	2	0	3	0	12	0.308
unidentified Fragilaria	0	3	3	0	2	0	0	0	0	0	0	0	8	0.205
Navicula pupula	1	0	0	2	0	0	1	0	0	0	1	2	7	0.179
Fragilaria construens + var	3	1	2	0	0	0	0	0	0	0	0	0	6	0.154
Amphora libyca	1	2	1	0	0	0	0	1	0	0	0	0	5	0.128
Epithemia adnata	2	0	0	0	0	0	0	2	0	1	0	0	5	0.128
Stephanodiscus cf. alpinus	0	0	0	0	1	3	0	0	0	0	0	0	4	0.103
Fragilaria crotonensis	0	0	1	0	0	0	0	0	0	0	0	2	3	0.077
Navicula gregaria	0	0	1	0	0	1	0	1	0	0	0	0	3	0.077
Navicula placentula	1	0	1	0	0	0	1	0	0	0	0	0	3	0.077
Navicula viridula	0	0	1	0	0	0	1	1	0	0	0	0	3	0.077
Rhopalodia novae zealandiae	1	0	0	0	0	0	0	0	0	0	1	1	3	0.077
Surirella spp	0	0	2	0	0	0	0	0	0	0	0	0	2	0.051
Amphora coffaeformis	0	0	1	0	0	0	0	0	0	0	0	0	1	0.026
Diploneis cf smithii	0	1	0	0	0	0	0	0	0	0	0	0	1	0.026
Stauroneis phoenicenteron	0	0	0	0	0	0	0	1	0	0	0	0	1	0.026
Chrysophycean cysts	0	0	0	0	0	0	0	0	0	0	0	1	1	0.026
Fragments of sponge spicules	5	8	9	0	1	0	3	3	0	2	6	0	37	0.949
DIATOM SUM	400	300	400	300	300	300	300	400	300	300	300	300	3900	100

Table A.4: Diatom counts for Rangitoto tephra section

Sample depth	44.25	42.75	39.75	38.75	37.75	36.75	35.75	34.75	33.75	30.75	29.75	28.75	27.75	26.75	25.75	23.75	21.75	19.75	SUM	%
Cyclotella stelligera	25	12	16	37	10	44	63	87	80	65	78	324	296	308	303	291	217	247	2503	34.764
Aulacoseira ambigua	245	293	263	149	303	164	100	71	96	52	71	19	14	18	11	17	56	0	1942	26.972
Synedra ulna	1	4	0	20	3	3	21	29	69	138	92	3	9	6	2	17	10	21	448	6.222
Stephanodiscuc spp	44	44	53	15	31	49	39	60	57	25	6	3	1	2	3	8	5	2	447	6.208
Fragilaria pinnata	10	7	32	75	22	36	34	38	17	18	36	19	14	8	9	5	13	30	423	5.875
Fragilaria crotonensis	7	9	0	2	4	0	12	15	32	60	31	0	0	0	0	0	0	0	172	2.389
Achnanthes cf. minutissima	0	0	0	1	0	0	0	0	1	2	0	1	12	9	18	14	20	26	104	1.444
Cocconeis placentula + vars	8	5	3	9	2	12	8	5	3	3	7	2	3	3	6	5	8	4	96	1.333
Navicula radiosa	0	2	0	4	1	5	3	0	1	3	8	7	9	4	12	8	13	3	83	1.153
Fragilaria construens + var	1	0	1	0	0	0	1	4	1	4	3	0	4	6	10	3	12	13	63	0.875
Achnanthes subatomoides	1	0	0	15	0	0	10	4	3	3	7	3	1	2	1	1	3	5	59	0.819
Achnanthes cleveii	1	3	3	3	2	1	3	5	4	6	2	1	1	3	2	1	2	10	53	0.736
Nitzschia spp.	8	2	7	3	2	1	4	0	1	0	3	1	0	0	1	2	4	10	49	0.681
Achnanthes exigua	5	2	2	3	3	3	2	8	1	3	3	2	0	2	0	0	3	2	44	0.611
unidentified Fragilaria	0	0	0	0	0	0	0	0	0	0	0	0	14	13	6	0	0	0	33	0.458
Rhopalodia novae zealandiae	0	0	0	0	0	0	0	0	0	0	0	2	5	3	3	8	7	3	31	0.431
Epithemia sorex	1	3	1	1	1	0	0	4	4	2	1	3	2	1	0	3	3	0	30	0.417
Achnanthes exigua v elliptica	0	0	0	0	0	0	0	0	0	0	10	4	2	0	1	1	0	8	26	0.361
Cymbella affinis	0	0	0	0	4	3	4	1	0	2	3	0	2	2	0	3	1	1	26	0.361
Navicula gregaria	3	3	0	2	1	1	1	0	0	2	0	1	4	2	0	0	3	2	25	0.347
Navicula cari	0	2	0	6	2	2	3	1	2	1	0	0	0	0	0	1	2	0	22	0.306
Fragilaria capucina v vaucheriae	0	0	0	0	0	0	0	2	0	0	15	0	0	0	0	0	0	0	17	0.236
Mastogloia elliptica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	7	0	17	0.236
Surirella spp	1	0	1	0	0	0	0	0	0	4	7	2	1	0	0	0	1	0	17	0.236
unidentified Navicula	0	0	0	0	0	0	0	0	11	2	2	0	0	0	0	0	0	0	15	0.208
Navicula placentula	2	0	0	0	0	3	0	0	0	0	3	0	0	0	1	1	3	0	13	0.181
Fragilaria brevistriata	0	0	0	5	1	1	2	0	1	1	0	0	0	0	0	0	0	0	11	0.153
Gomphonema parvulum	1	1	2	0	2	0	0	2	0	0	0	0	1	0	0	0	0	2	11	0.153
Navicula bacillum	0	0	0	0	0	2	0	0	1	0	1	0	0	1	1	2	1	0	9	0.125
Navicula pupula	0	1	0	1	1	0	0	0	0	0	0	1	0	2	1	0	2	0	9	0.125
Pinnularia spp.	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2	2	1	1	8	0.111
Unidentified Aulacoseira	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	6	0.083
Cyclotella meneghenlana	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	4	0.056
Epithemia adnata	0	0	0	0	0	1	0	0	0	0	2	0	0	0	1	0	0	0	4	0.056
Fragilaria zeilleri	2	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	4	0.056
Navicula viridula	0	0	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	4	0.056
Achnanthes lanceolata v frequentissima	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0	0	0	0	3	0.042
Amphora libyca	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0.028
Diploneis cf smithii	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2	0.028
Navicula cuspidata	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2	0.028
Stauroneis phoenicenteron	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0.028
Cymbella cistula	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.014
Diploneis cf subovalis	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0.014
Eunotia spp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0.014
Navicula seminulum	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0.014
unidentified Achnanthes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0.014
Lycopodium spores	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	2	0.028
Chrysophycean cysts	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0.056
Fragments of sponge spicules	28	7	12	47	5	68	89	59	14	3	7	1	3	1	0	1	3	2	350	4.861
DIATOM SUM	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	7200	100

Table A.5: Diatom counts for P40(T5) tephra section

Sample depth	6109.45	6107.45	6106.45	6105.45	6104.45	6103.45	6102.45	6101.75	6100.75	6099.75	6098.75	6097.75	6096.75	6094.75	6092.75	6089.75	SUM	%
Cyclotella stelligera	331	372	376	386	392	387	379	374	393	384	389	367	390	386	388	378	6072	94.875
Synedra ulna	5	17	16	3	1	6	10	12	2	0	0	22	2	4	0	6	106	1.656
Fragilaria capucina v vaucheriae	57	1	0	2	1	0	0	1	0	0	0	0	0	0	0	0	62	0.969
Cocconeis placentula + vars	4	4	1	2	3	4	2	4	3	4	3	1	1	2	4	2	44	0.688
Gomphonema parvulum	0	2	1	1	1	0	0	1	1	5	2	0	3	1	3	4	25	0.391
Fragilaria pinnata	0	0	1	1	0	1	1	4	0	5	1	1	2	4	1	1	23	0.359
Achnanthes exigua	0	1	1	0	1	1	1	0	1	0	1	2	0	1	0	5	15	0.234
Achnanthes cf. minutissima	0	1	1	0	0	0	1	0	0	1	1	4	1	0	2	2	14	0.219
Nitzschia spp.	1	0	2	1	0	0	1	1	0	0	1	1	0	0	1	1	10	0.156
Navicula radiosa	1	0	0	1	0	0	0	1	0	0	0	1	0	0	1	0	5	0.078
Achnanthes cleveii	0	0	0	1	0	0	0	0	0	0	2	0	0	1	0	0	4	0.063
Epithemia adnata	0	1	0	1	0	0	0	0	0	0	0	0	0	1	0	1	4	0.063
Amphora libyca	1	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	3	0.047
Cymbella affinis	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	3	0.047
Navicula gregaria	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	2	0.031
Epithemia sorex	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0.016
Navicula placentula	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0.016
Navicula viridula	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0.016
Fragments of sponge spicules	0	1	1	1	0	0	0	2	0	0	0	0	0	0	0	0	5	0.078
DIATOM SUM	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	6400	100

Table A.6: Diatom counts for P36(T6) tephra section

Sample depth	5547.75	5545.75	5544.75	5543.75	5542.75	5541.75	5540.75	5539.75	5538.75	5537.75	5536.75	5535.75	5534.75	5532.75	5530.75	5527.75	SUM	%
Cyclotella stelligera	223	268	267	201	106	227	276	175	263	293	278	356	352	242	238	312	4077	63.703
Synedra ulna	41	29	103	183	282	17	10	87	105	95	114	35	11	3	4	2	1121	17.516
Synedra ulna v spathulifera	121	86	26	4	4	145	86	10	0	0	0	0	25	136	139	41	823	12.859
Cocconeis placentula + vars	0	1	0	1	1	4	8	37	5	0	0	1	2	5	5	10	80	1.250
Gomphonema parvulum	0	5	0	1	0	0	2	27	2	3	1	0	0	0	3	12	56	0.875
Fragilaria pinnata	3	0	0	5	2	1	5	13	3	4	0	2	2	4	3	5	52	0.813
Achnanthes cleveli	4	3	0	2	4	1	3	5	3	0	2	1	5	3	3	2	41	0.641
Achnanthes exigua	3	2	0	1	0	0	1	3	2	2	3	0	0	0	0	1	18	0.281
Epithemia sorex	0	1	0	0	0	1	0	6	0	1	0	0	0	0	3	6	18	0.281
Nitzschia spp.	1	0	0	0	0	0	2	7	2	0	0	0	0	2	0	3	17	0.266
Cymbella affinis	0	0	0	0	0	0	0	7	3	1	1	1	0	1	1	0	15	0.234
Achnanthes cf. minutissima	0	0	1	2	1	3	1	2	0	0	0	1	0	1	0	2	14	0.219
Stephanodiscus cf. alpinus	0	0	3	0	0	0	0	3	5	0	0	0	0	0	0	1	12	0.188
Epithemia adnata	0	0	0	0	0	1	0	6	0	0	0	0	0	0	0	1	8	0.125
Navicula radiosa	0	1	0	0	0	0	1	2	0	0	0	2	0	0	1	1	8	0.125
Fragilaria construens + var	0	3	0	0	0	0	0	0	2	0	0	0	0	2	0	0	7	0.109
Fragilaria crotonensis	2	1	0	0	0	0	0	3	0	0	0	0	0	0	0	0	6	0.094
Aulacoseira ambigua	2	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	5	0.078
Fragilaria capucina v vaucheriae	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	4	0.063
Amphora coffaeformis	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	0.031
Amphora libyca	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	0.031
Navicula placentula	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	2	0.031
Surirella spp	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	2	0.031
Achnanthes lanceolata v frequentissima	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0.016
Fragilaria zeilleri	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0.016
Navicula gregaria	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0.016
Navicula pupula	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0.016
Navicula viridula	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0.016
Pinnularia divergens	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0.016
Fragments of sponge spicules	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	1	4	0.063
DIATOM SUM	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	6400	100

Table A.7: Diatom counts for P36(T4) tephra section

Sample depth	5494.45	5492.45	5491.45	5490.45	5489.45	5488.45	5487.45	5486.25	5485.25	5484.25	5483.25	5482.25	5481.25	5479.25	5477.25	5474.25	SUM	%
Cyclotella stelligera	306	348	302	256	243	253	202	269	276	263	214	245	275	236	262	358	4308	67.313
Synedra ulna v spathulifera	0	1	82	118	124	109	148	0	102	116	165	133	6	103	112	25	1344	21.000
Synedra ulna	74	45	5	5	14	20	38	114	6	7	9	7	103	45	6	2	500	7.813
Fragilaria pinnata	3	0	3	5	4	6	3	3	6	6	3	3	1	4	3	2	55	0.859
Cocconeis placentula + vars	1	2	1	8	2	1	2	1	1	2	4	3	3	3	7	5	46	0.719
Gomphonema parvulum	4	0	1	3	5	2	1	9	3	0	3	3	1	1	4	5	45	0.703
Achnanthes cleveli	3	0	2	2	2	4	1	1	4	2	0	1	2	2	2	2	30	0.469
Achnanthes exigua	0	1	0	0	3	1	2	0	1	1	0	1	1	1	2	0	14	0.219
Fragilaria construens + var	4	2	0	0	0	1	0	2	0	0	1	0	3	0	0	0	13	0.203
Achnanthes cf. minutissima	0	0	1	1	0	0	0	0	0	2	1	1	0	4	2	0	12	0.188
Nitzschia spp.	2	0	0	0	0	1	2	0	1	1	0	1	0	0	0	1	9	0.141
Navicula pupula	0	0	0	0	0	2	0	1	0	0	0	1	1	0	0	0	5	0.078
Epithemia sorex	0	0	0	1	1	0	1	0	0	0	0	0	2	0	0	0	5	0.078
Navicula radiosa	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	4	0.063
Epithemia adnata	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	3	0.047
Amphora libyca	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	3	0.047
Aulacoseira angustissima	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.016
Cymbella affinis	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0.016
Navicula gregaria	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0.016
Navicula placentula	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.016
DIATOM SUM	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	6400	100

Table A.8: Diatom counts for P36(T3) tephra section

Sample depth	5489.25	5487.25	5486.25	5485.25	5484.25	5483.25	5482.25	5481.25	5480.25	5479.25	5478.25	5477.25	5476.25	5474.25	5472.25	5469.25	SUM	%
Cyclotella stelligera	229	249	257	250	272	272	243	211	321	282	290	236	291	282	272	341	4298	67.156
Synedra ulna	159	132	120	132	110	114	142	165	64	103	95	152	94	96	114	41	1833	28.641
Cocconeis placentula + vars	2	7	9	2	2	3	4	3	1	4	6	1	3	10	4	4	65	1.016
Fragilaria pinnata	2	4	5	4	5	6	2	5	5	2	0	1	2	3	0	4	50	0.781
Gomphonema parvulum	1	2	4	3	2	1	0	2	5	3	5	2	3	2	1	4	40	0.625
Achnanthes exigua	2	2	3	4	5	1	2	7	3	1	1	0	4	0	0	0	35	0.547
Achnanthes cf. minutissima	1	1	0	0	2	1	2	4	0	2	0	2	0	0	1	1	17	0.266
Achnanthes cleveii	0	0	0	0	0	1	1	1	0	0	0	3	1	2	1	0	10	0.156
Nitzschia spp.	2	2	0	0	0	0	0	0	1	1	3	0	0	2	1	0	12	0.188
Fragilaria construens + var	0	0	0	0	0	0	0	0	0	0	0	0	1	1	4	1	7	0.109
Eunotia formica	0	0	0	4	2	0	0	0	0	0	0	0	0	0	0	0	6	0.094
Epithemia sorex	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	2	5	0.078
Navicula radiosa	0	1	1	0	0	0	1	0	0	0	0	1	0	0	2	0	6	0.094
Cymbella affinis	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	1	3	0.047
Navicula pupula	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	3	0.047
aulacoseira ambigua	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	2	0.031
Epithemia adnata	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	2	0.031
Amphora libyca	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0.016
Eunotia spp.	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0.016
Fragilaria zeilleri	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0.016
Navicula placentula	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0.016
Neidium iridis	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.016
Stephanodiscus cf. alpinus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0.016
DIATOM SUM	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	6400	100

Table A.9: Diatom counts for P36(T2) tephra section

Sample depth	5477.25	5475.25	5474.25	5473.25	5472.25	5471.25	5470.25	5449.75	5448.75	5447.75	5446.75	5445.75	5444.75	5442.75	5440.25	5437.25	SUM	%
Cyclotella stelligera	213	275	212	242	242	266	322	330	324	310	337	345	331	263	254	285	4551	71.109
Synedra ulna	173	102	172	139	133	122	68	54	66	79	52	45	58	121	125	105	1614	25.219
Cocconeis placentula + vars	5	9	7	4	4	1	4	2	4	1	1	3	5	9	5	2	66	1.031
Fragilaria pinnata	2	1	3	4	5	1	1	4	2	1	4	0	3	0	3	4	38	0.594
Achnanthes exigua	4	4	1	1	4	1	1	4	0	3	1	3	1	1	4	1	34	0.531
Gomphonema parvulum	1	0	2	0	3	3	0	0	1	2	1	1	0	1	3		18	0.281
Achnanthes cf. minutissima	0	0	0	0	4	2	2	2	1	2	0	0	0	0	1	2	16	0.250
Epithemia sorex	1	2	0	2	1	1	0	1	0	0	1	0	0	0	1	1	11	0.172
Navicula radiosa	0	1	1	1	1	1	1	1	1	1	0	0	1	1	0	0	11	0.172
Nitzschia spp.	0	1	1	3	1	0	1	1	0	0	1	2	0	0	0	0	11	0.172
Aulacoseira ambigua	0	2	0	0	2	0	0	0	0	0	0	0	0	0	2	0	6	0.094
Navicula gregaria	1	1	0	1	0	0	0	1	0	0	1	1	0	0	0	0	6	0.094
Cymbella affinis	0	0	0	0	0	2	0	0	0	0	0	0	0	1	1	0	4	0.063
Navicula viridula	0	0	1	0	0	0	0	0	0	1	0	0	0	1	0	0	3	0.047
unidentified Fragilaria	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	3	0.047
Epithemia adnata	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0.016
Eunotia spp.	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0.016
Fragilaria crotonensis	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.016
Navicula placentula	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0.016
Navicula pupula	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0.016
Rhopalodia novae zealandiae	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.016
Stauroneis phoenicenteron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0.016
Surirella spp	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0.016
DIATOM SUM	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	6400	100